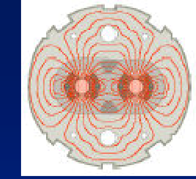


The Large Hadron Collider

(presented to Pulsed Power 2009, 22nd September 2009)

Stephen Myers

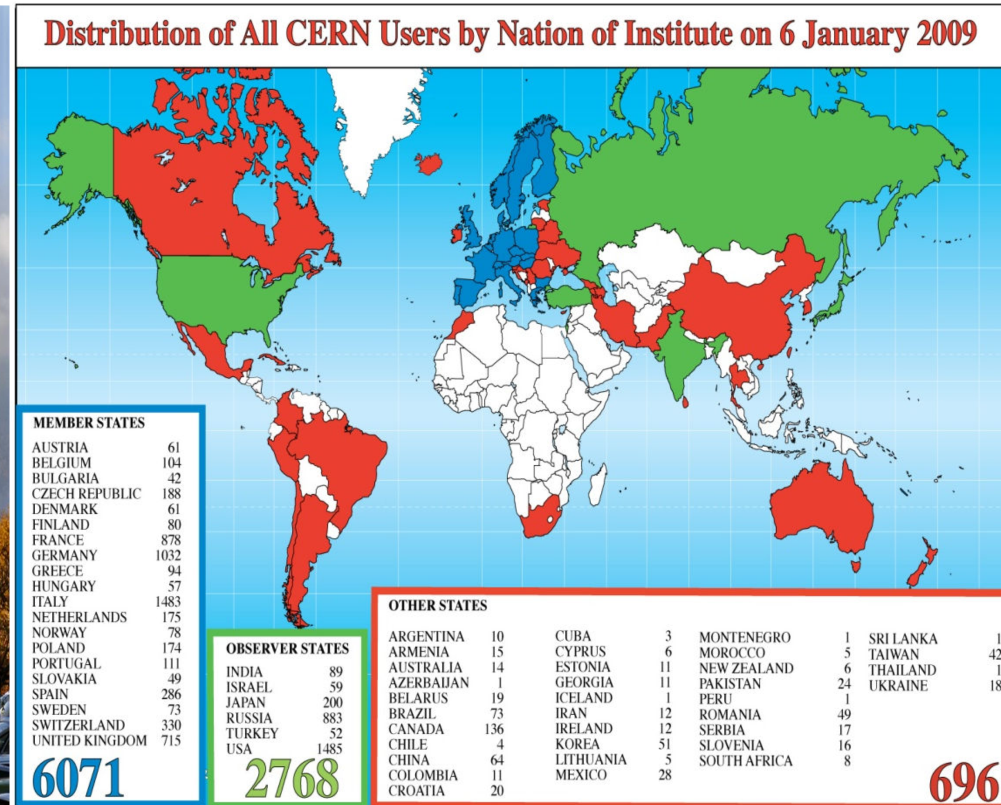
Director for Accelerators and Technology,

CERN Geneva

What is CERN?

Born in 1954 in Geneva, Switzerland

Now the World's largest laboratory for research into Particle Physics



20 European Member States and around 60 other countries collaborating

Around 10 000 scientists from around the world at CERN

CERN in Numbers

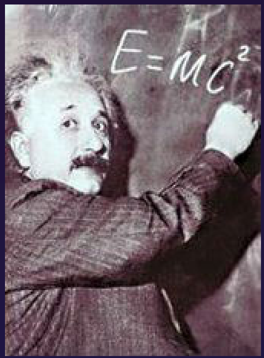
- 2256 staff
- ~700 other paid personnel
- 9535 users
- Budget (2009) 1100 MCHF

- 20 Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
- 1 Candidate for Accession to Membership of CERN: Romania
- 8 Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and Unesco

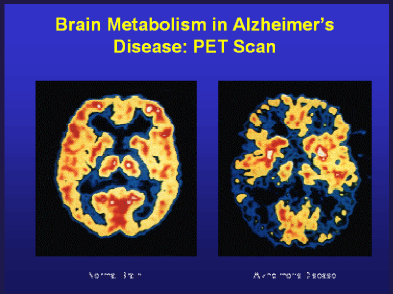
Innovation Education
CERN
uniting people
Research

The Mission of CERN

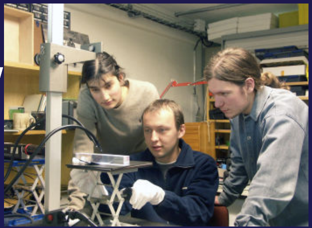
- **Push back** the frontiers of knowledge
  - E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?
  - Builds particle accelerators/colliders and experimental detectors



- **Develop** new technologies
  - Accelerator and detector related technologies
  - Information technology - the Web and the GRID
  - Medicine - diagnosis and therapy

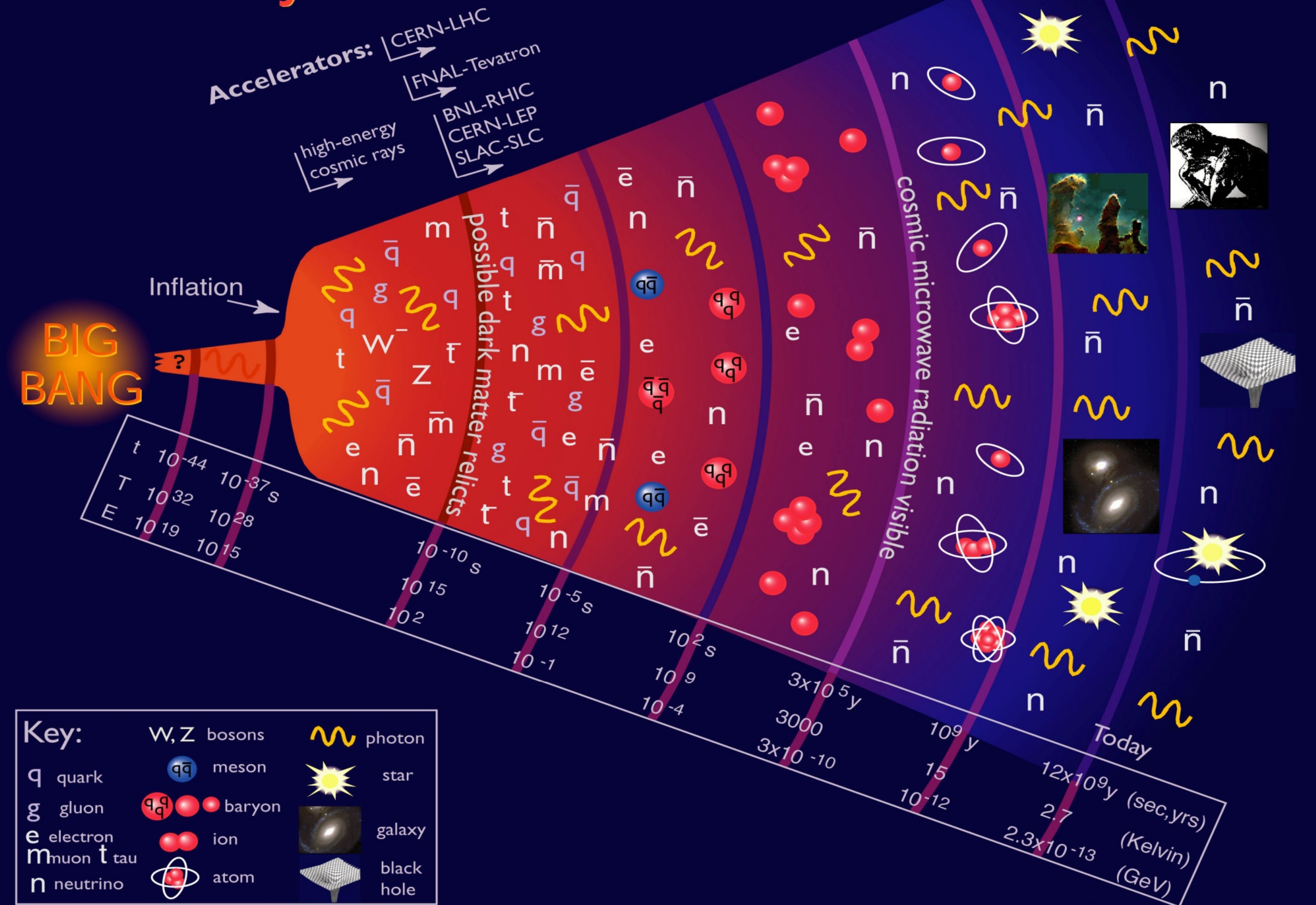


- **Train** scientists and engineers of tomorrow



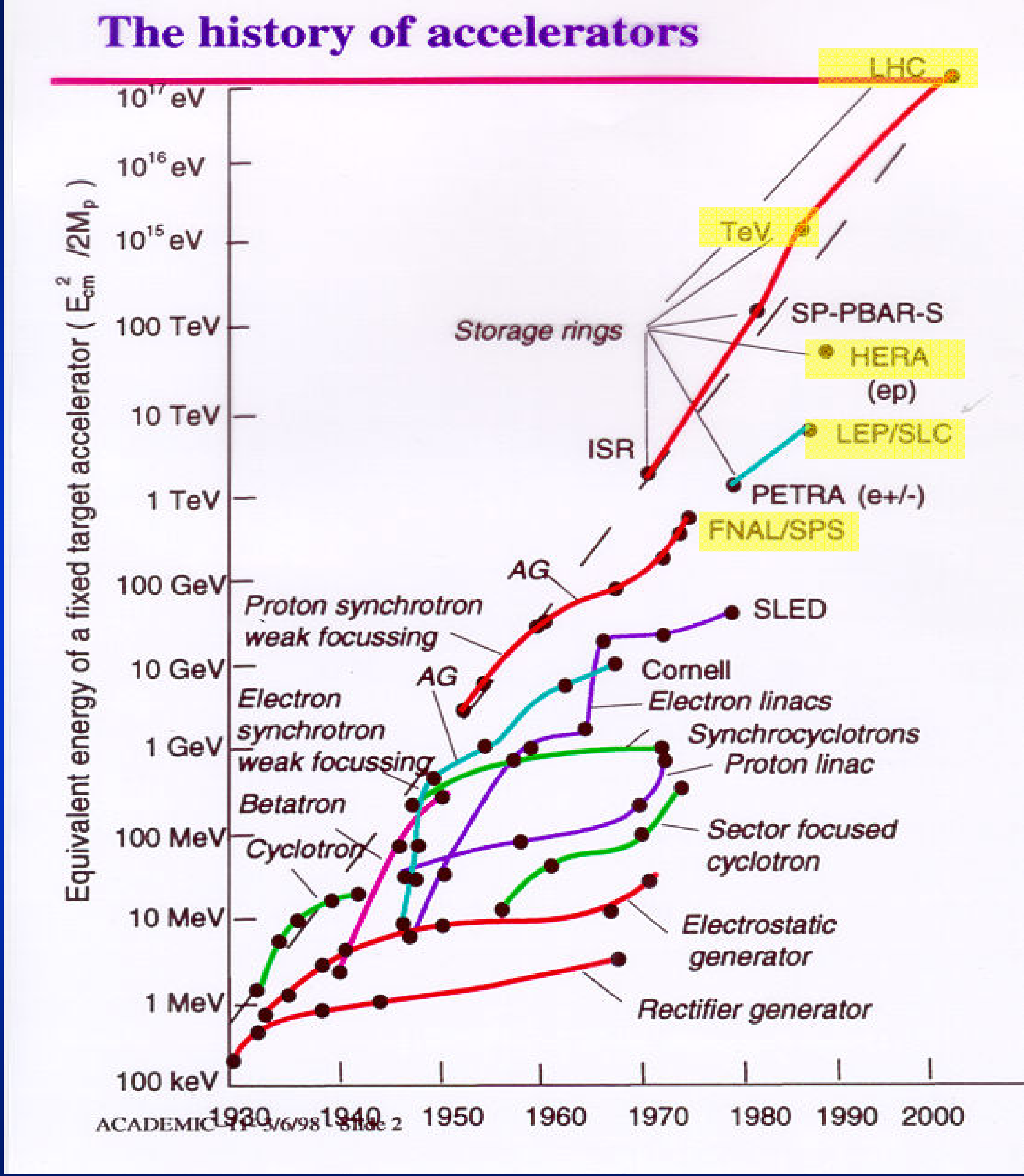
- **Unite** people from different countries and cultures

History of the Universe

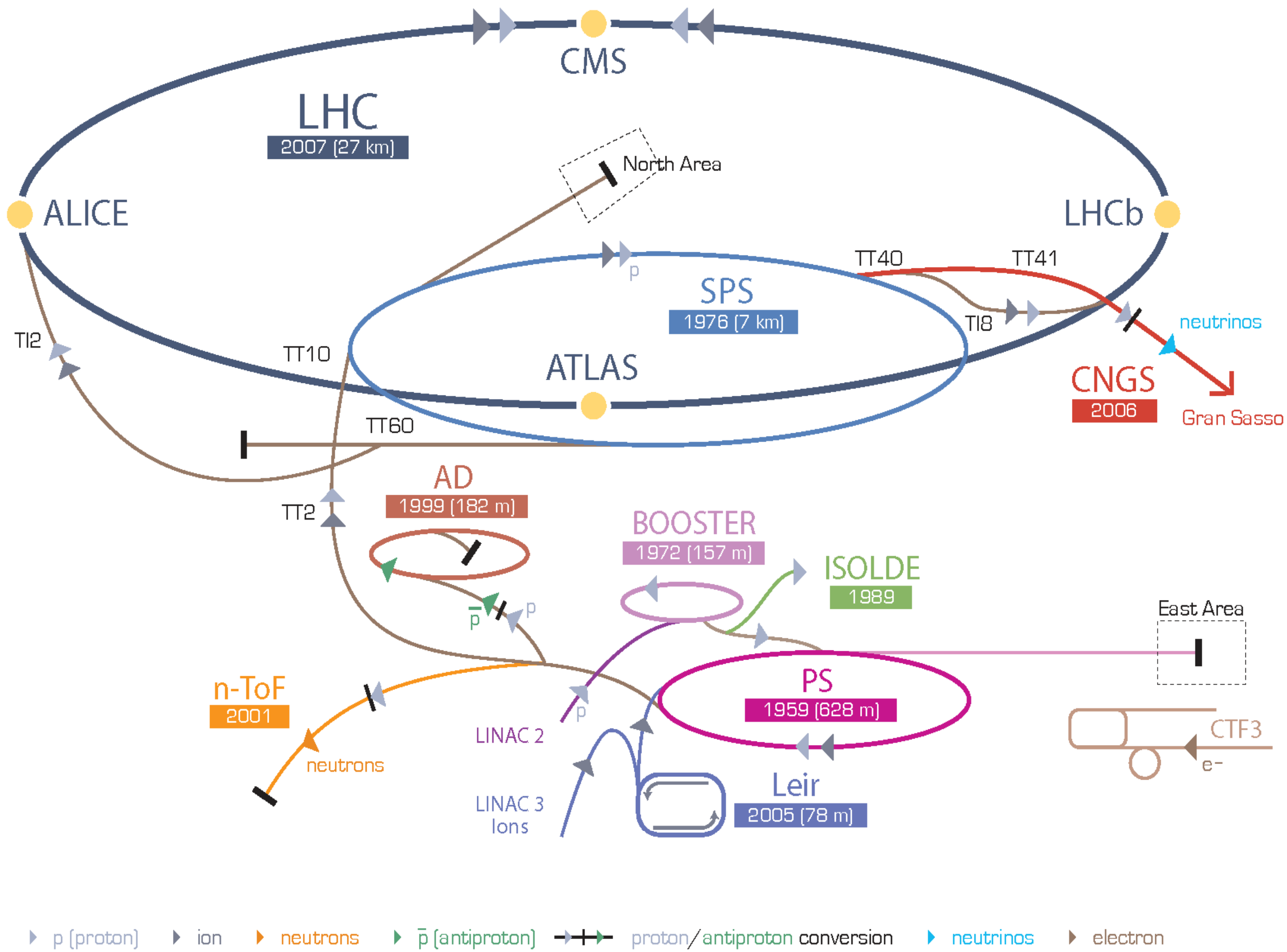


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

- sustained exponential development for more than 79 years
- progress achieved through repeated jumps from saturating to emerging technologies
- superconductivity, key technology of high-energy machines since the 1980s



CERN Accelerator Complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

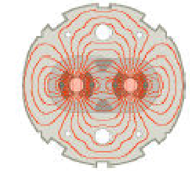
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

LHC What is it?

Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985

Basic Parameters of LHC



- ## Beam Energy
  - **For maximum beam energy you need maximum bending field and the maximum radius of curvature (existing tunnel)**

$$E_{beam} = 0.3\ B\ r$$

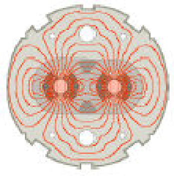
$$\underset{[GeV]}{} \qquad \underset{[T]}{} \quad \underset{[m]}{}$$

[GeV] [T] [m]

  - **7TeV/beam needs more than 8.3Tesla, i.e. sc magnets**

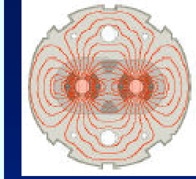
- ## Luminosity
  - **For discovery potential we want the maximum number of collisions therefore the maximum number of protons colliding**
    - **Maximum beam current**

LHC: Some Technical Challenges



Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 2kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

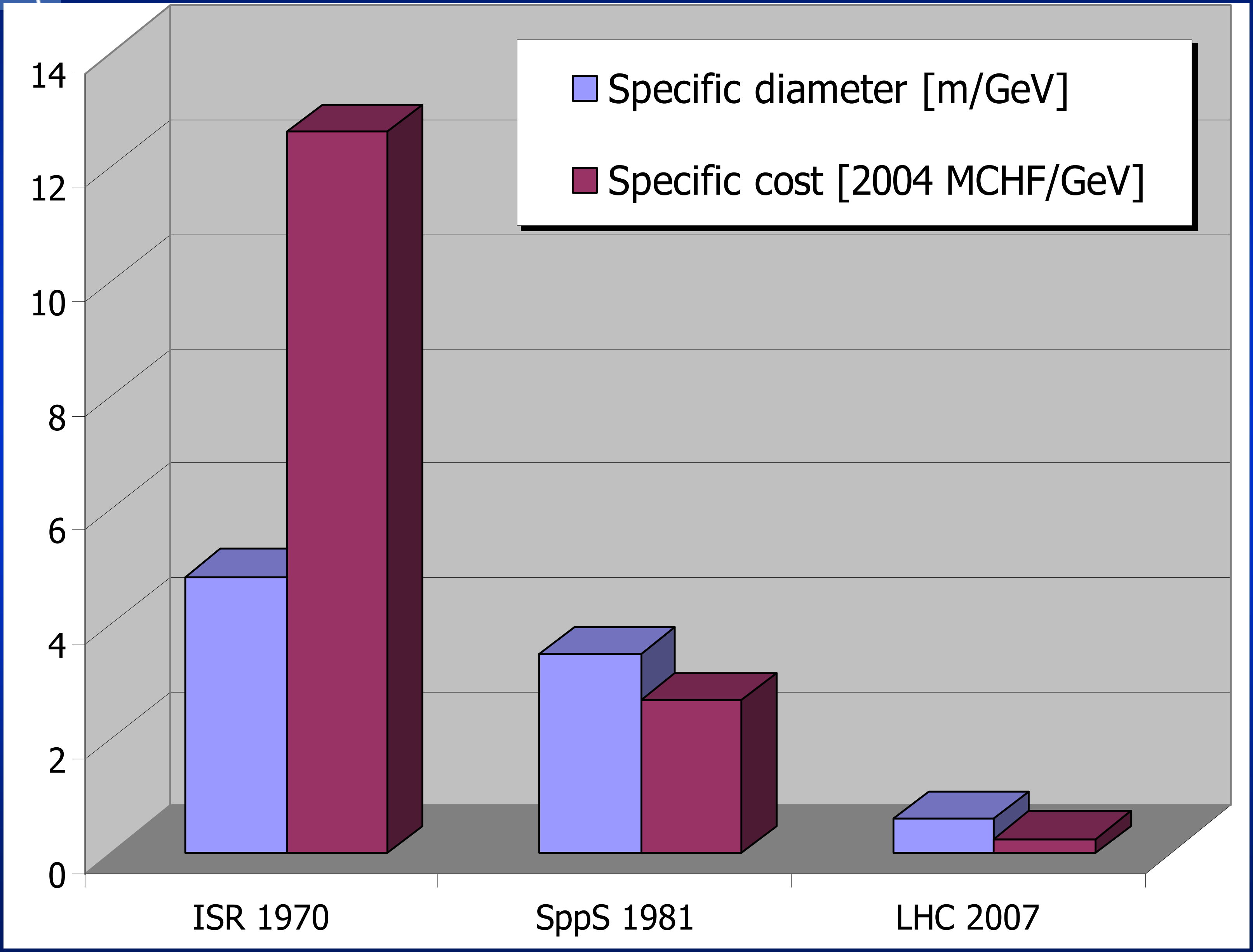
If the LHC did not use superconductivity



The LHC has a circumference of 26.7 km, with 20km filled with superconducting magnets operating at 8.3 T. The refrigerators producing the liquid helium to cool the magnets consume 40 MW of power.

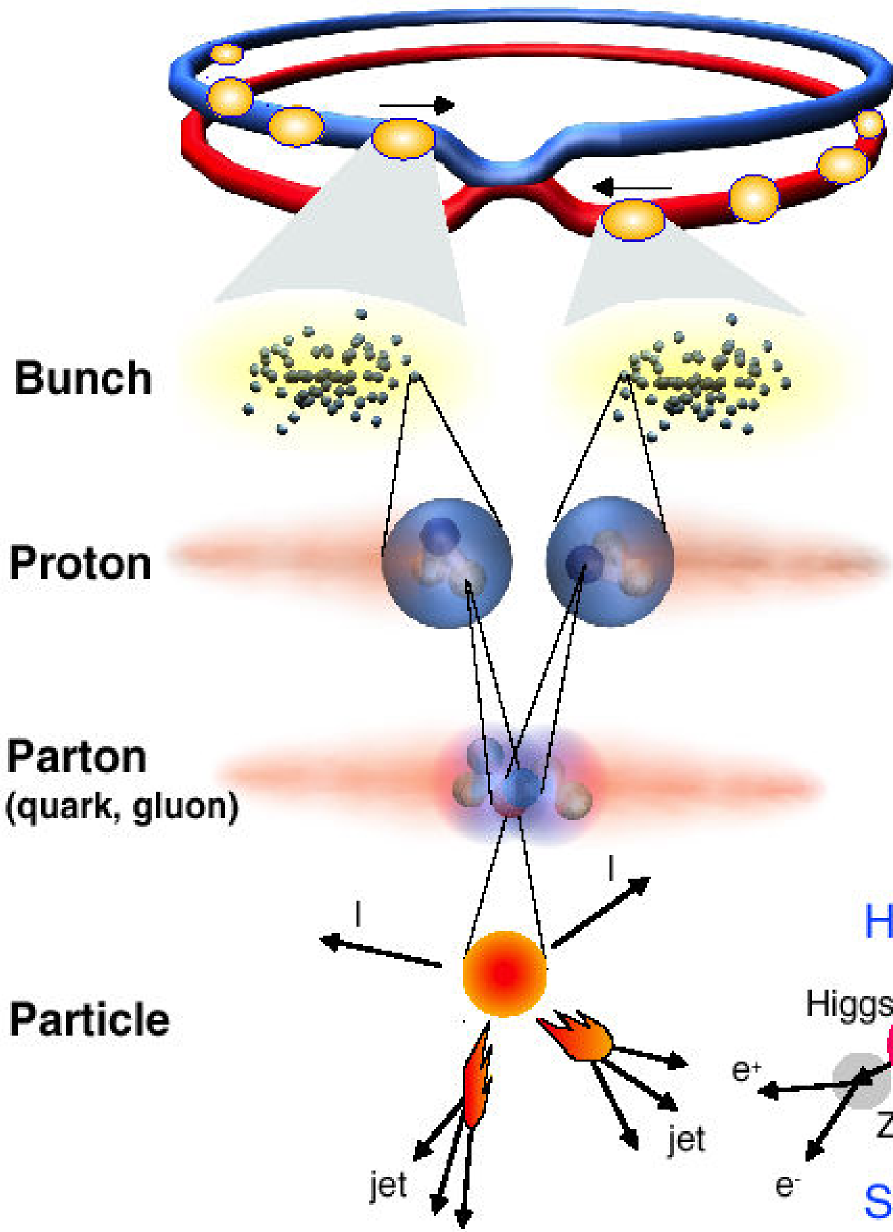
An equivalent machine with classical electromagnets would have a circumference of 100 km and would consume 1000 MW of power.

Specific Cost and Diameter of Particle Colliders over 40years

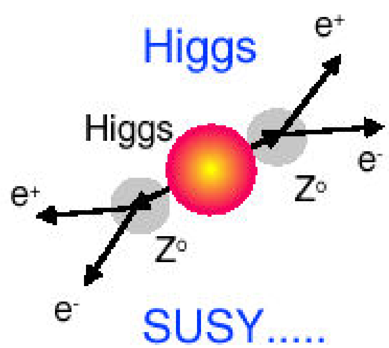


Critical Parameters

Collisions at LHC

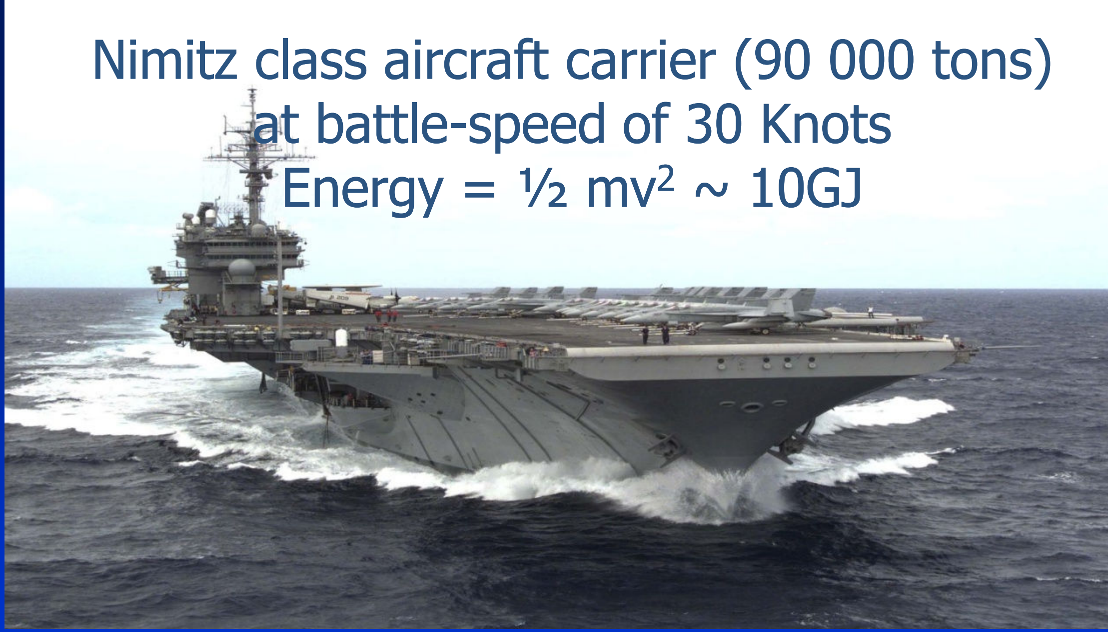


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz



Selection of 1 in 10,000,000,000,000

So what is LHC ?



Nimitz class aircraft carrier (90 000 tons)
at battle-speed of 30 Knots
Energy = ½ mv^2 ~ 10GJ

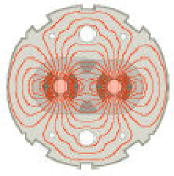
- Big
- Cold
- Complex
- Very powerful
    - Nominal performance
        - Energy stored in the magnets — 10 GJ (1100 MJ/octant)
        - Energy stored in each beam — 362 MJ (in 89us) 4TW (power)

Copper
Melting point 1356 K
Specific heat capacity 386 J kg^{-1} K^{-1}
Latent heat of fusion 205000 J kg^{-1}

So to heat and melt 1kg takes (1354*386+205000) J =0.73MJ

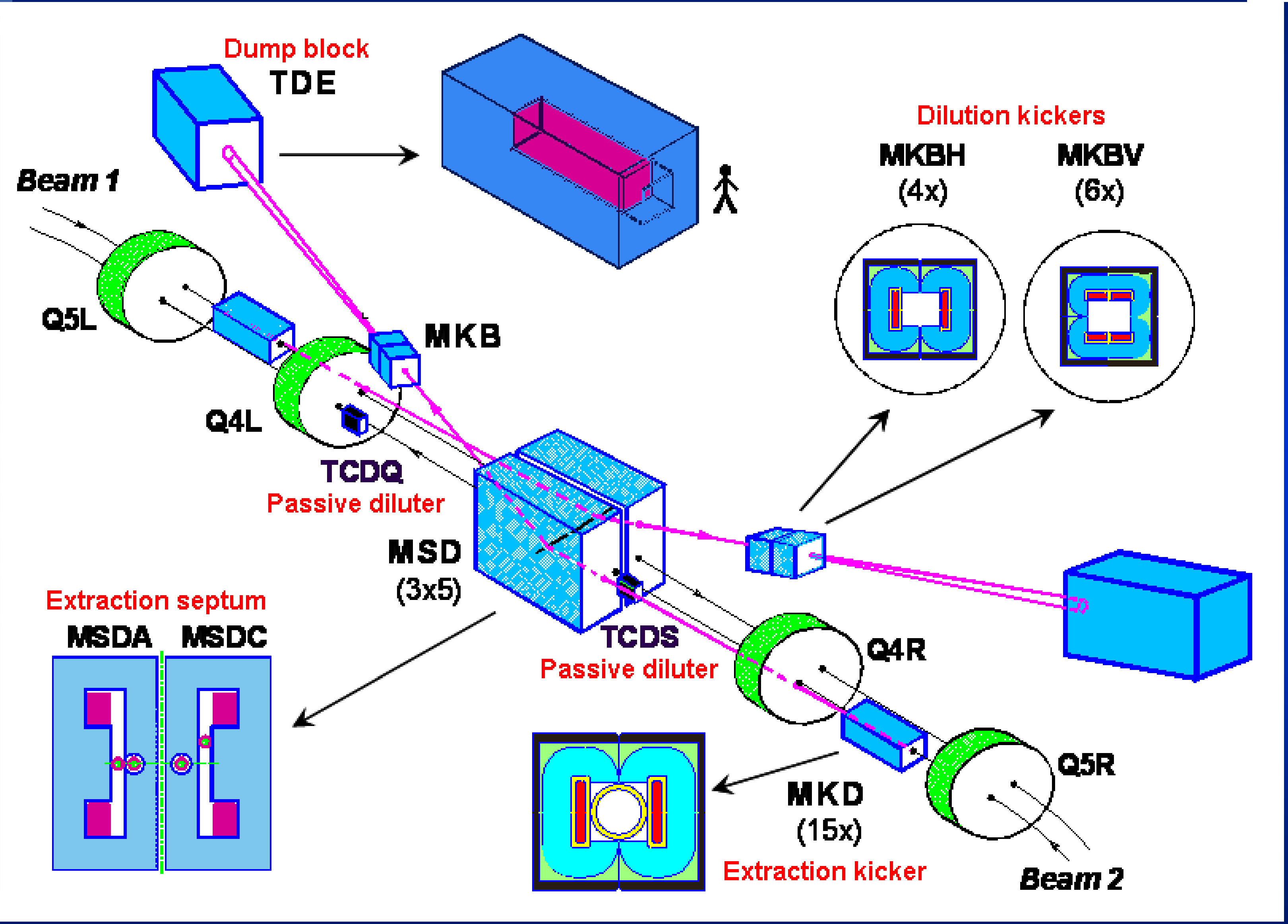
362MJ could heat and melt half a tonne (500kg) of copper
1100MJ could heat and melt 1.5 tonne (1500kg) of copper

How to Deal with the LHC self Destructive Power



- In case of a problem the stored energy in the magnets and in the beam must be transferred to and dissipated in a safe, clearly defined place
- Magnet Protection system
  - "Quench" Protection (measures resistance)
  - Energy dump triggered and energy dissipated as heat in resistors (after of course aborting the beams)
- Machine Protection System
  - All critical elements which could provoke a beam loss are equipped with an emergency beam abort signal which triggers the beam dump system. There is also a beam loss monitoring system all around the circumference which will abort the beam if anomalous losses occur
  - The beam dump system is the last safety net

LHC beam dump principle (and acronyms)

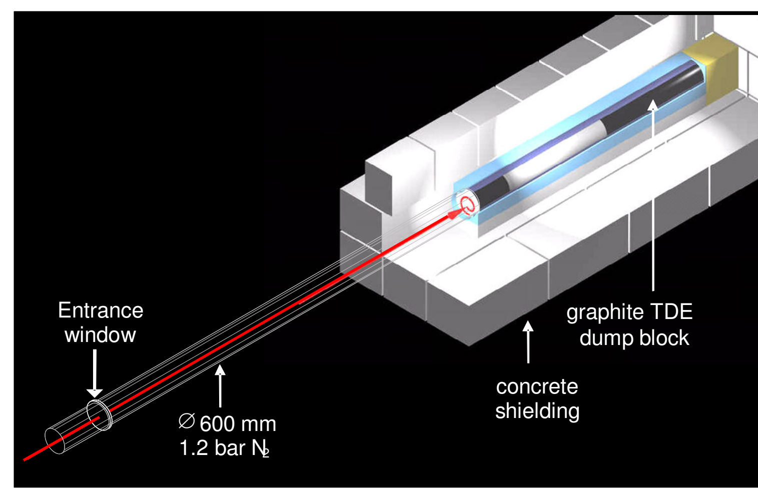


Extraction Kicker parameters

Number of magnets per system..................... 15
System deflection angle................... 0.275 mrad
Kick strength per magnet................... 0.428 Tm
Vacuum chamber clear aperture (inner diameter) ....56 mm
Operating charging voltage range..... 2 to 30 kV
Magnet field overshoot at 7 TeV........... ≤7.9 %
Magnet field overshoot at 450 GeV.... ≤10.0 %
Field flat top duration.......................... ≥ 90 μs
Effective magnet length (magnetic) .....1.421 m
Yoke length (mechanical)................... 1.348 m
Magnet vacuum length (mechanical)... 1.583 m
Kicker rise time...................... ....3 μs

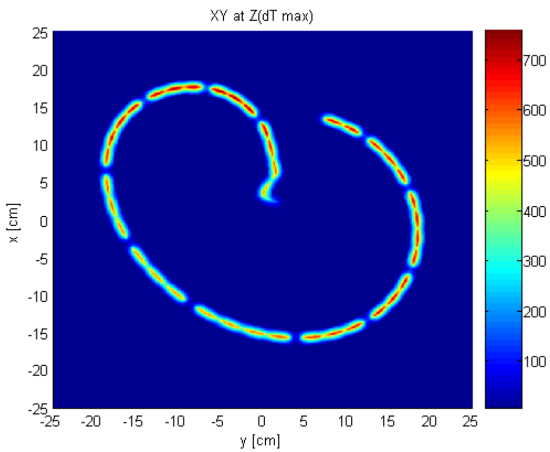
Beam dump core (TDE)

- 7.7m long, 700 mm ∅ graphite core
- Graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, filled with 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks

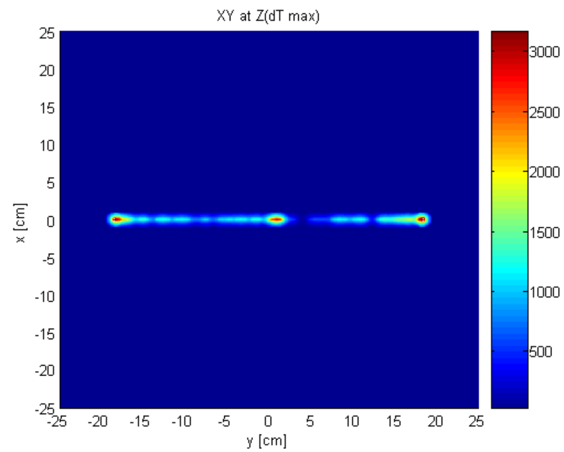


Beam dump core with dilution failures

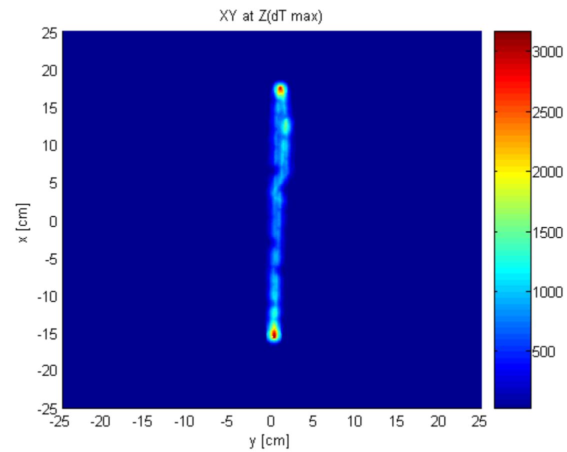
Nominal



0/6 vertical diluters



0/4 horizontal diluters



Nominal beam intensity (3.2×10^{14} p+)

Maximum energy density in dump block

		number active MKBV						
	kJ/g	6	5	4	3	2	1	0
number active MKBH	4	**1.09**	1.17	1.28	1.65	2.44	4.25	7.96
	3	1.33	1.38	1.45	1.67	2.43	4.32	**8.98**
	2	1.74	1.75	1.85	2.01	2.50	4.50	**11.30**
	1	2.74	2.89	2.87	2.99	3.36	4.74	**16.03**
	0	6.67	7.56	**8.41**	**9.90**	**12.70**	**17.44**	**53.29**

Maximum temperature rise in dump block

		number active MKBV						
	K	6	5	4	3	2	1	0
number active MKBH	4	**761**	804	867	1060	1455	2308	**3727**
	3	894	919	954	1069	1451	2340	**3727**
	2	1105	1110	1164	1244	1482	2425	**3727**
	1	1603	1670	1661	1720	1895	2534	**3727**
	0	3397	**3727**	**3727**	**3727**	**3727**	**3727**	**Vapour**

31 kJ/g for onset of sublimation, 60 kJ/g for complete vaporization

LHC Beam Dumping System

MKD:
2 x 15 Systems

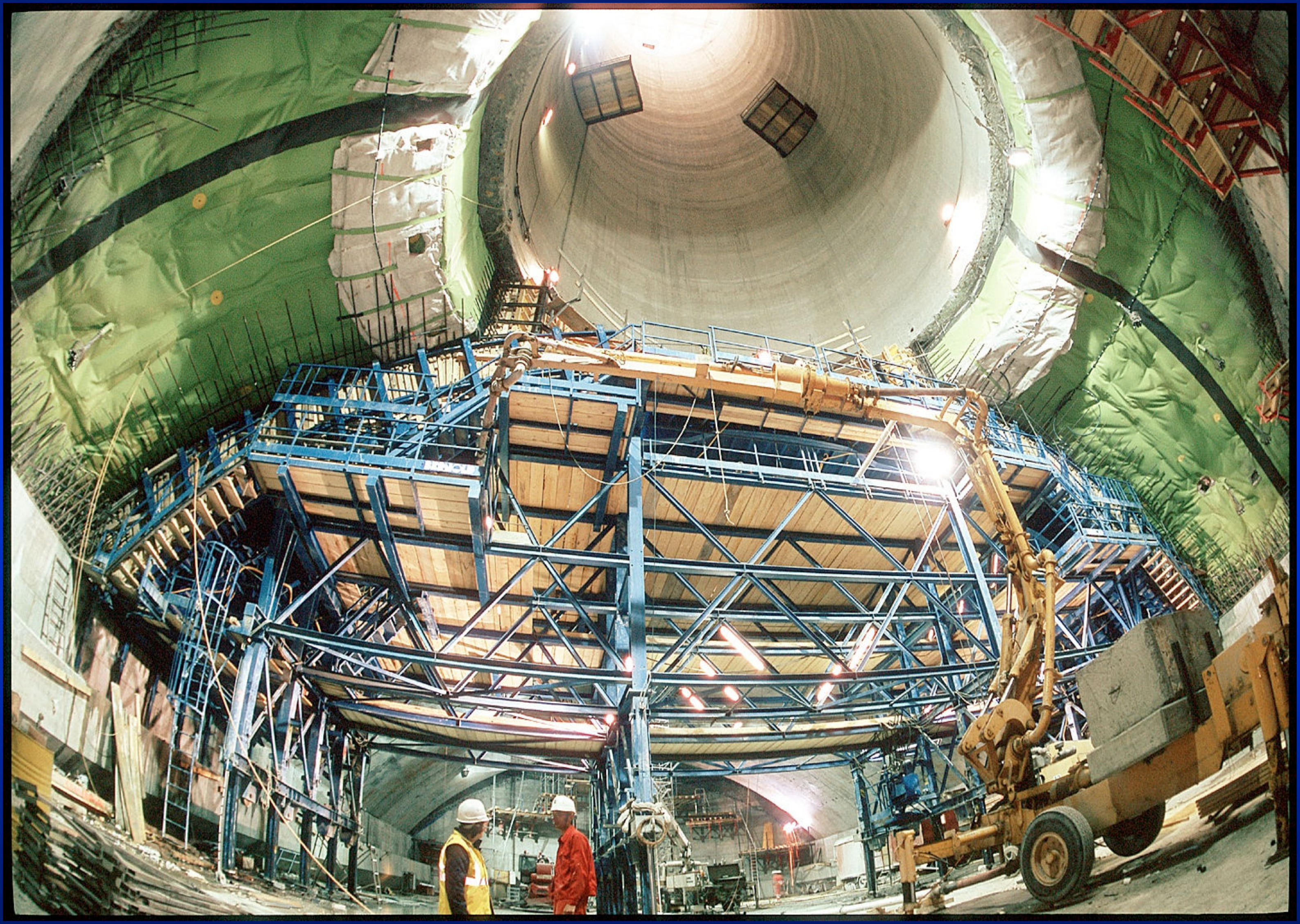
Magnet operates in air with coated ceramic chambers

Civil Engineering ATLAS

Excavating the vast underground cavern to house the ATLAS experiment at CERN´s LHC collider. 100 m underground, it will be as high as a six-storey bulding

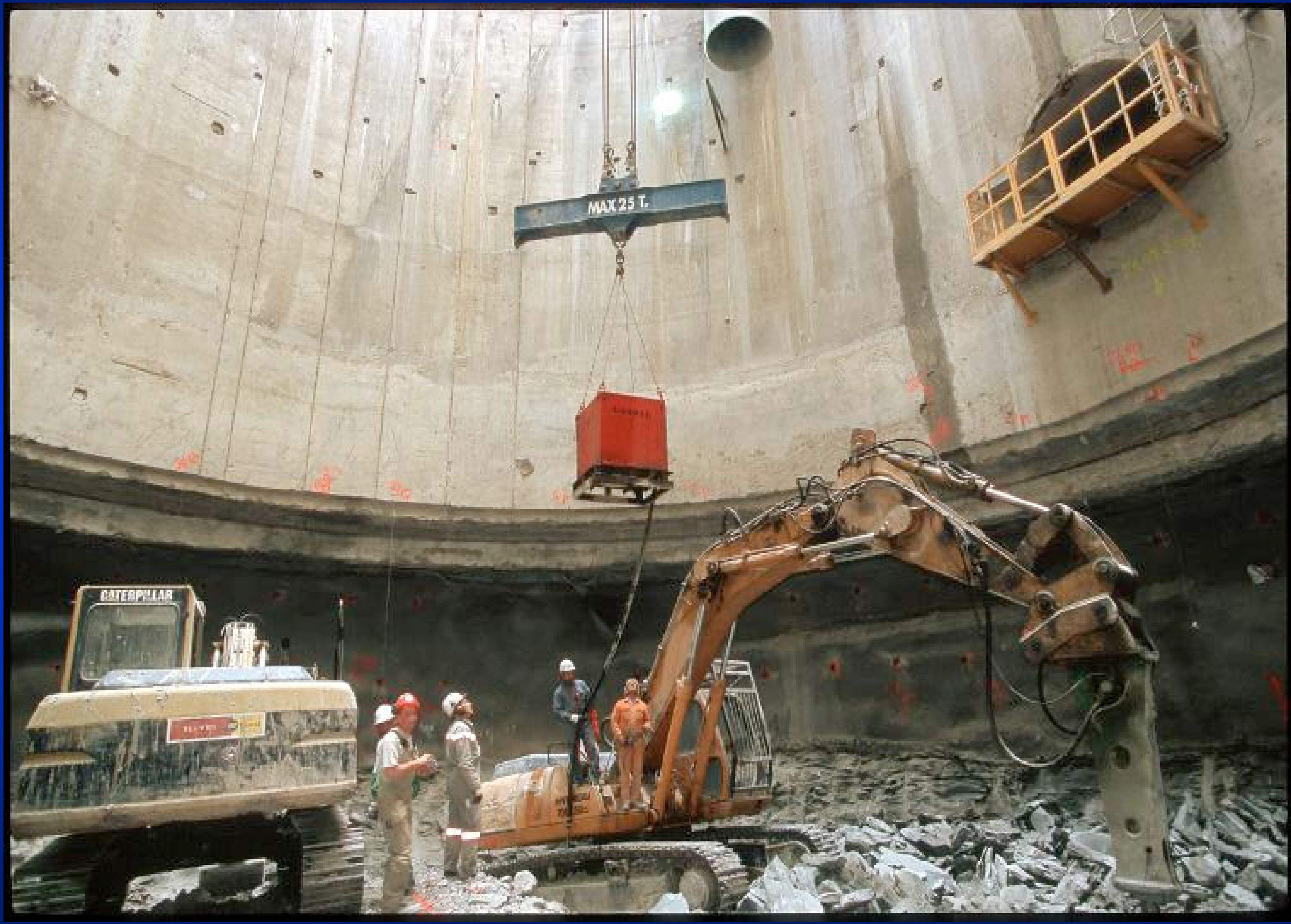
Civil Engineering Atlas cavern

Civil engineering works at Point 1 for ATLAS detector (LHC) : the UX15 Cavern. The 35 m span for the ATLAS detector hall is one of the longest underground spans ever constructed. The ceiling of the 1.380 m2 cavern "hangs" from a system of ground anchors installed from galleries excavated laterally from the access shafts.



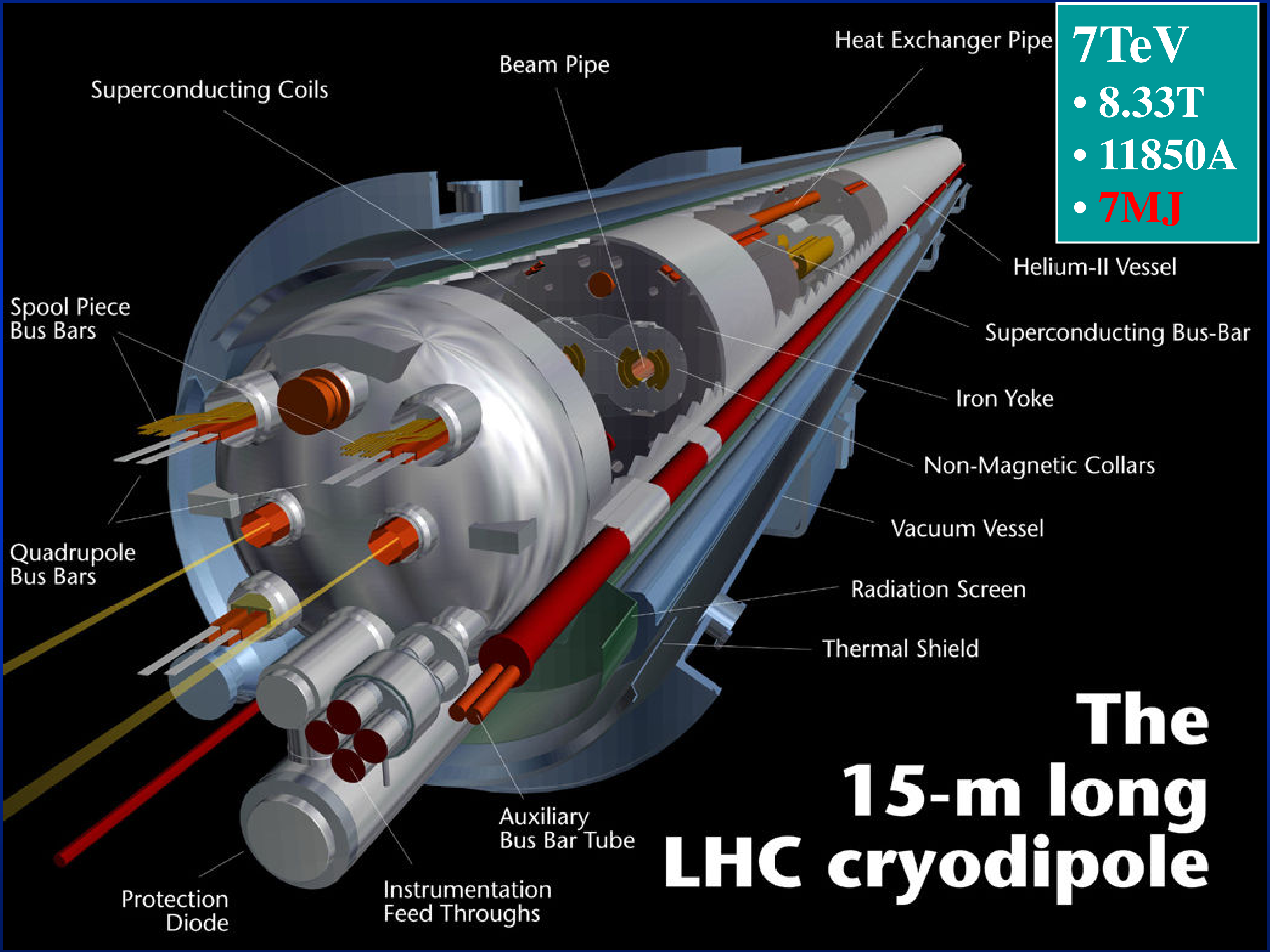
Civil Engineering CMS

Civil Engineering CMS



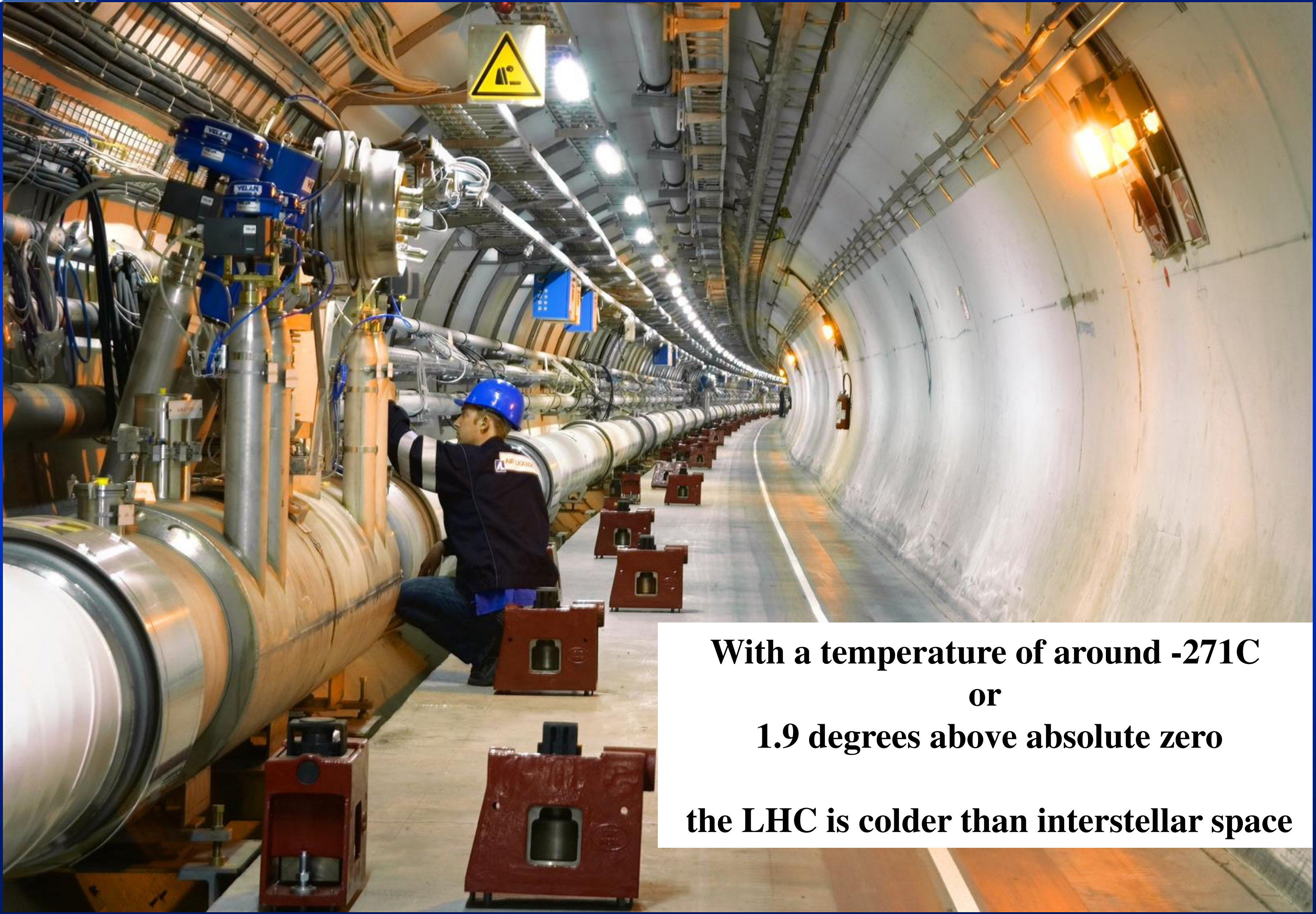
LHC dipoles (1232 of them) operating at 1.9K

Contracts by 4.7cm during cool-down



7TeV
- 8.33T
- 11850A
- 7MJ

Helium distribution line has to go in first

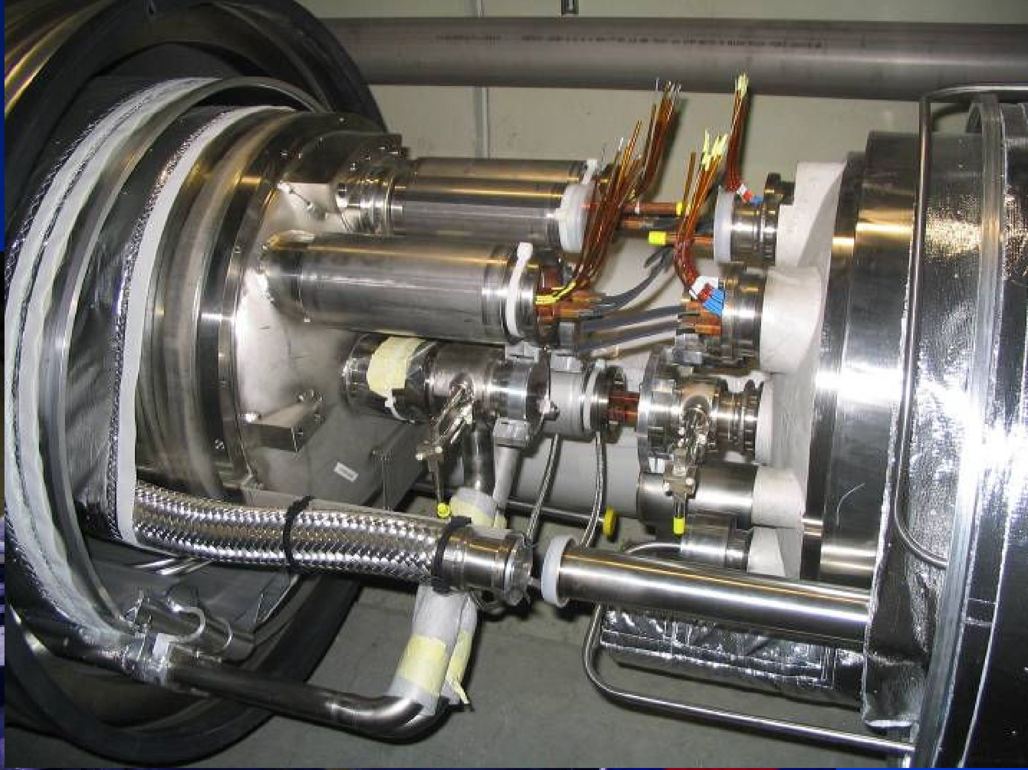


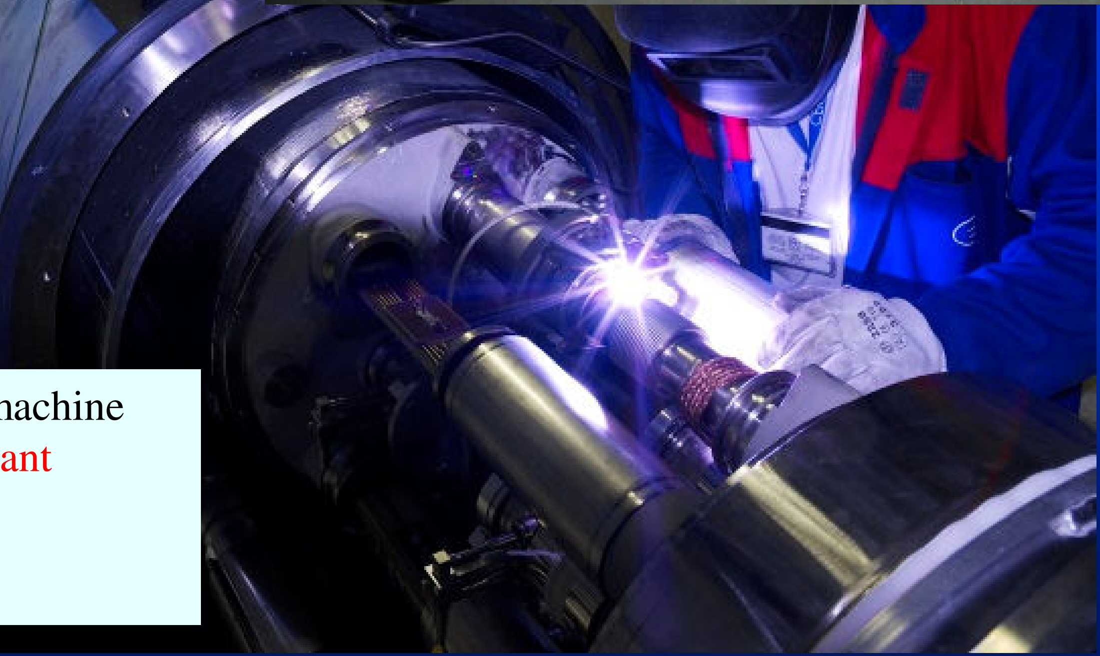
With a temperature of around -271C
or
1.9 degrees above absolute zero

the LHC is colder than interstellar space

Magnets follow

Interconnections





During cool-down of the LHC the machine contracts by 80 metres, 10m per octant

- Vacuum continuity
- Electrical connections

The Large Hadron Collider

What is it (for) ?

Construction

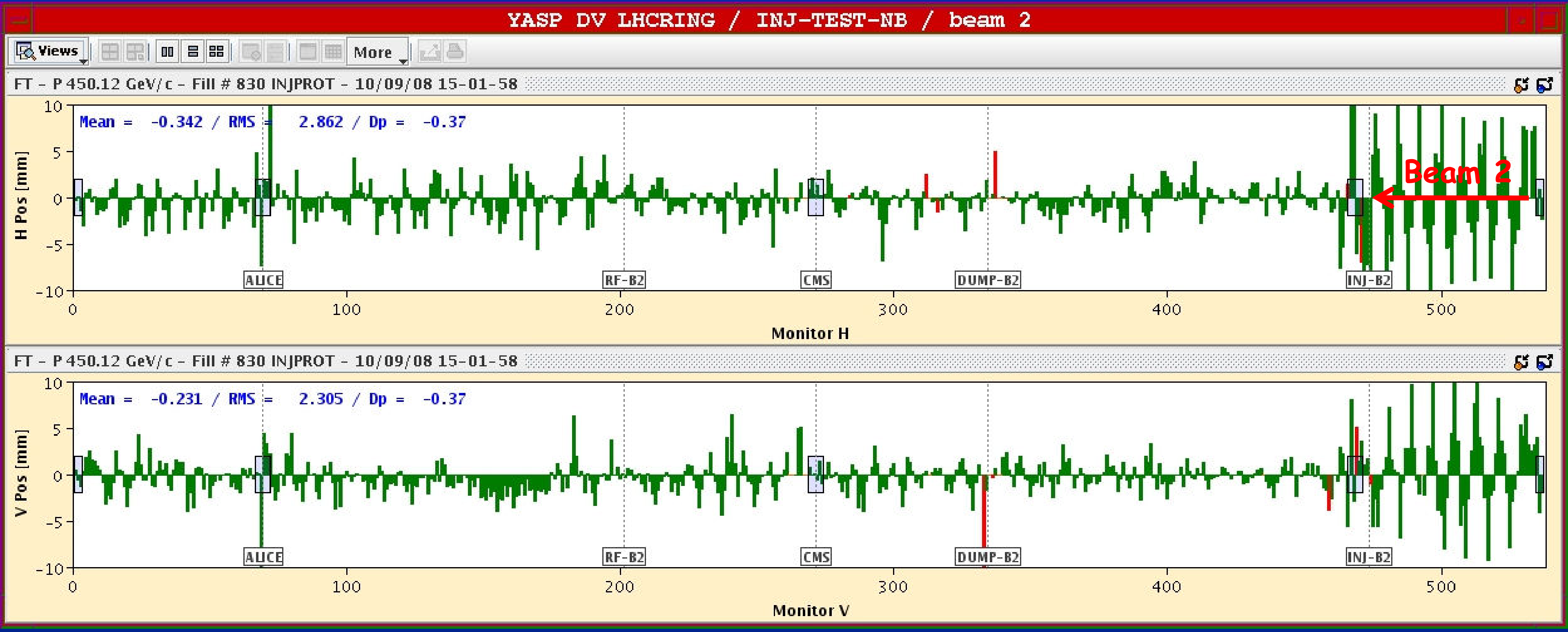
Beam

Breakdown

Prospects


September 10

Measure and correct – first turn trajectory steering



The Large Hadron Collider

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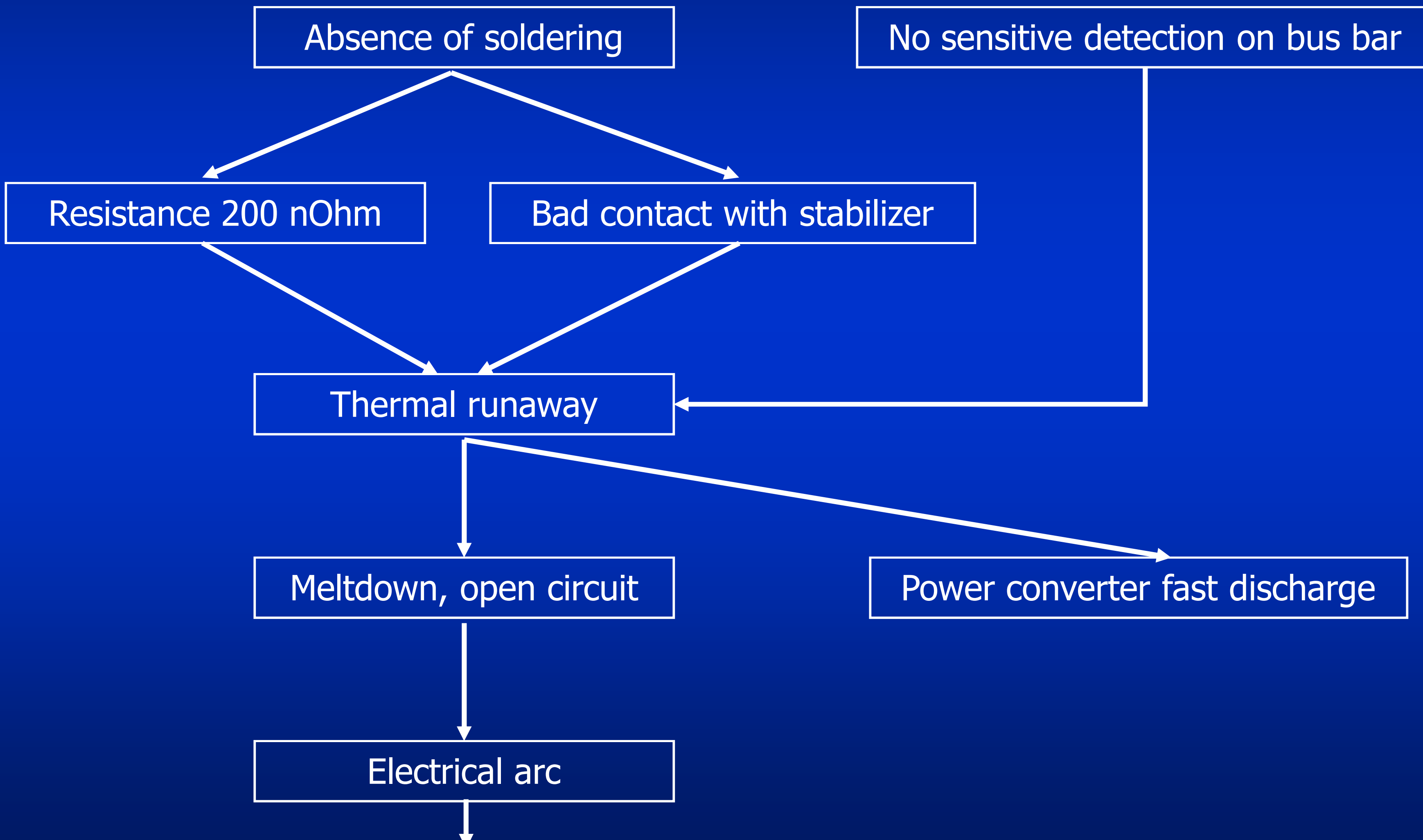
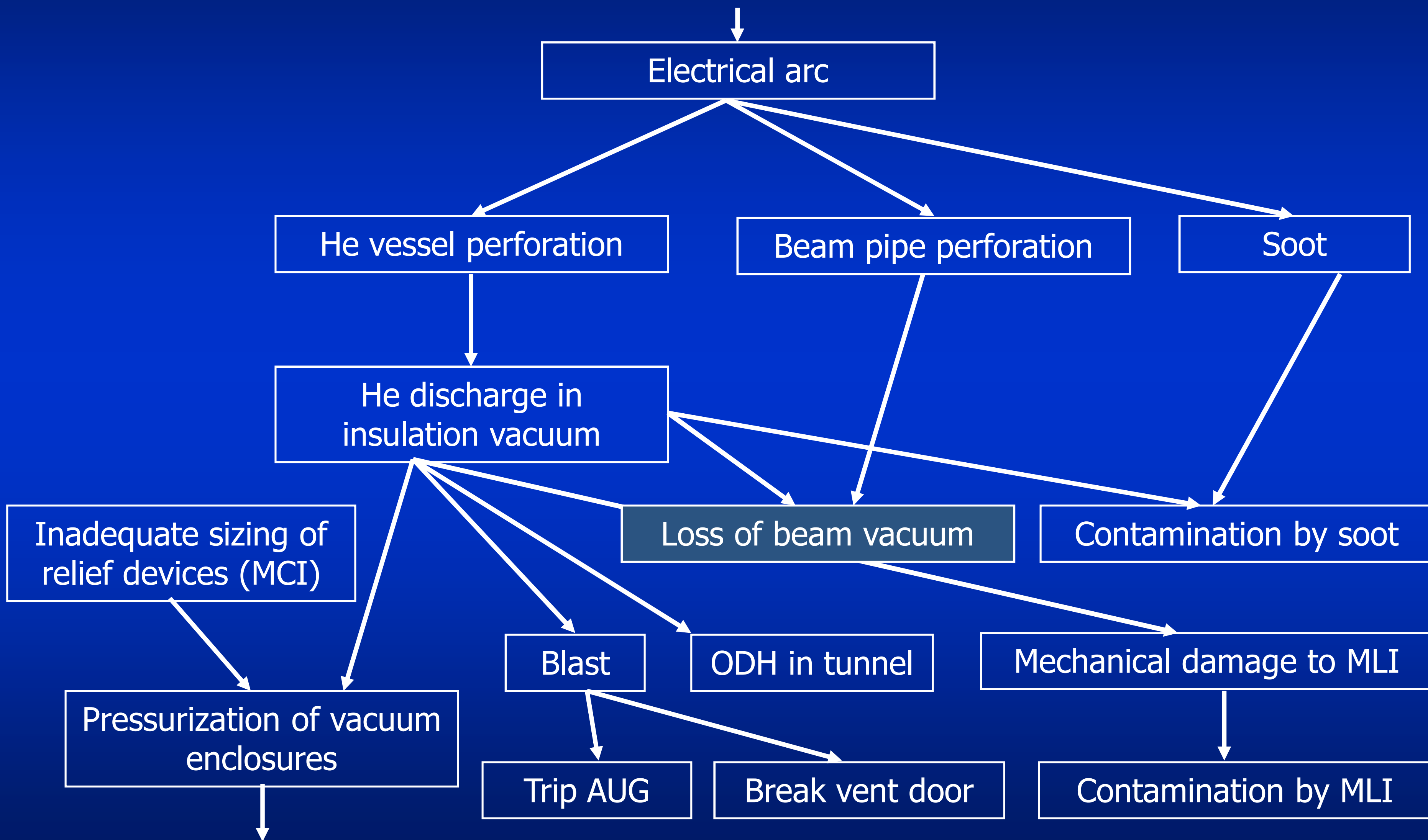
Incident of September 19th 2008

- During a few days period without beam
- Making the last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
- Electrical arc developed which punctured the helium enclosure
- Helium released into the insulating vacuum
- Rapid pressure rise inside the LHC magnets
  - Large pressure wave travelled along the accelerator both ways
  - Self actuating relief valves opened but could not handle all
  - Large forces exerted on the vacuum barriers located every 2 cells
  - These forces displaced several quadrupoles and dipoles
  - Connections to the cryogenic line affected in some places
  - Beam vacuum also affected

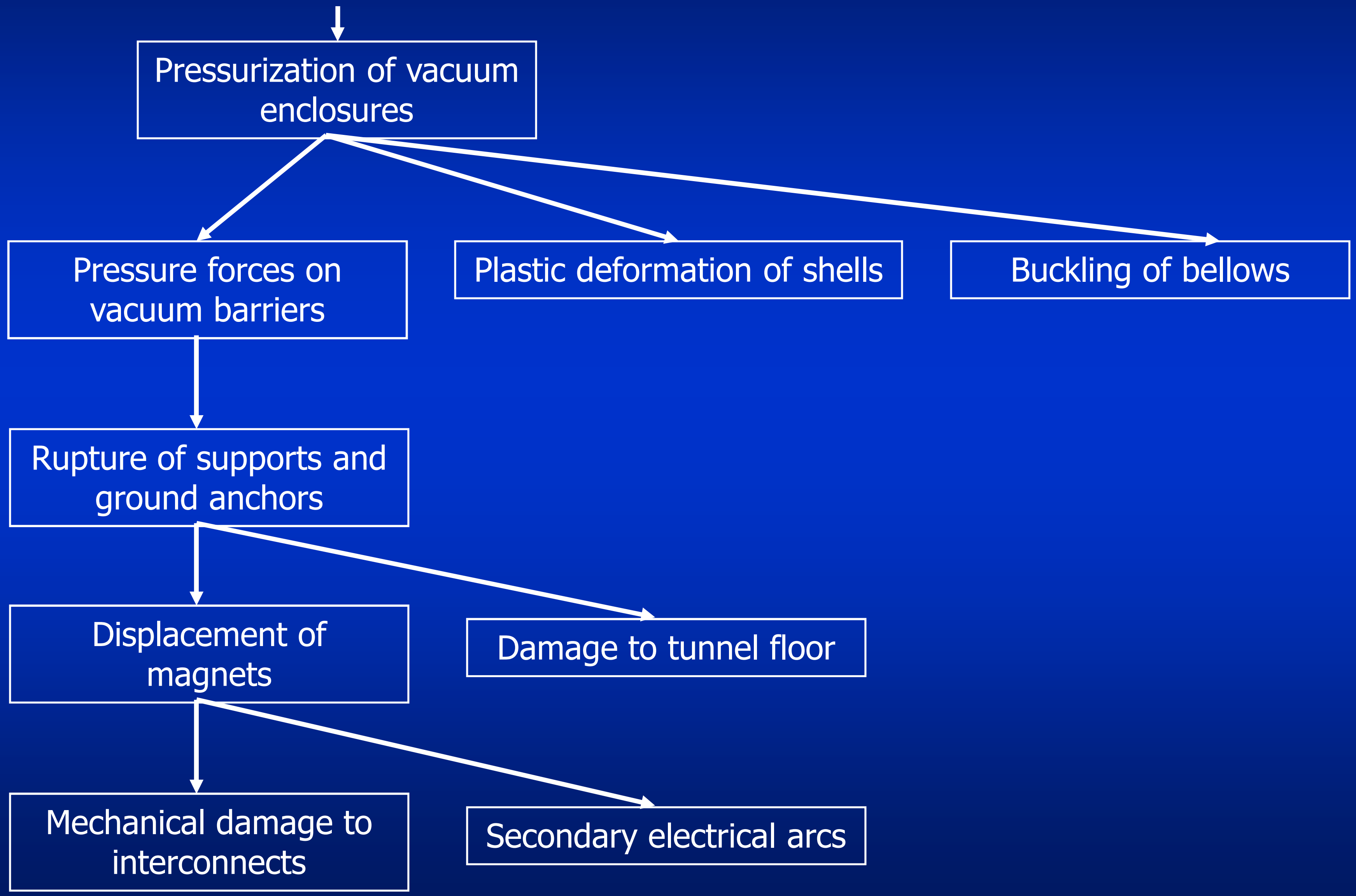
Fault tree [1/3]



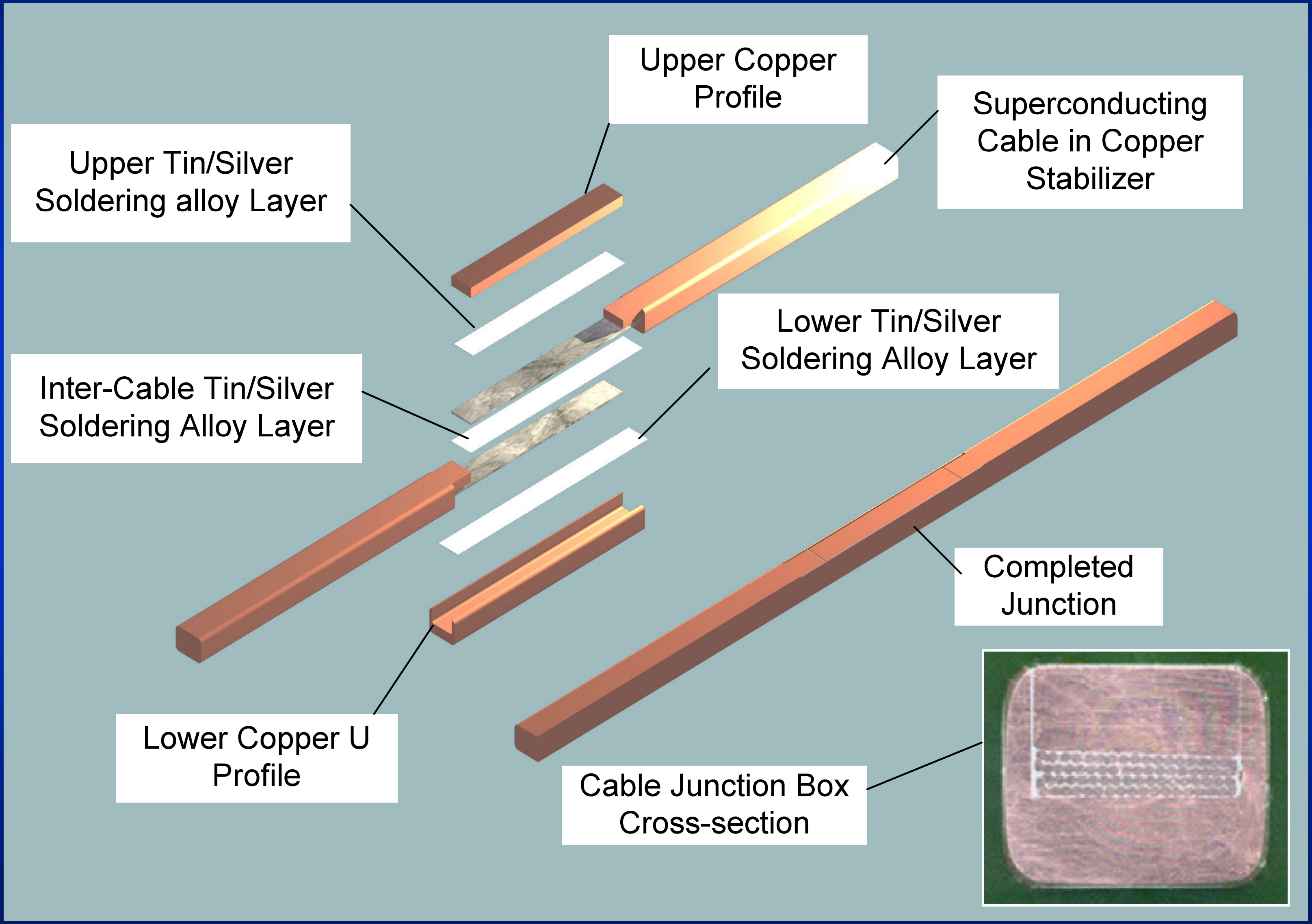
Fault tree [2/3]



Fault tree [3/3]



Bus bar splice

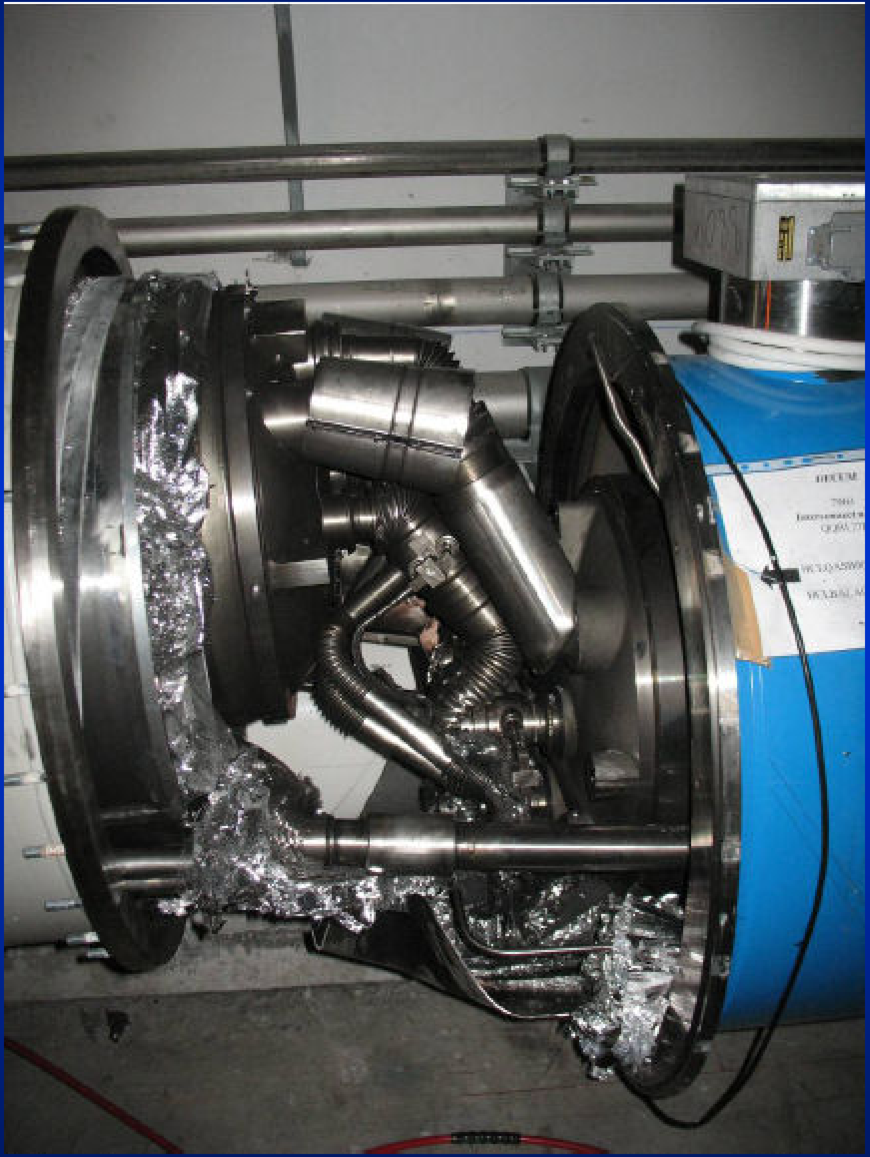


Repair of QRL service module in S3-4

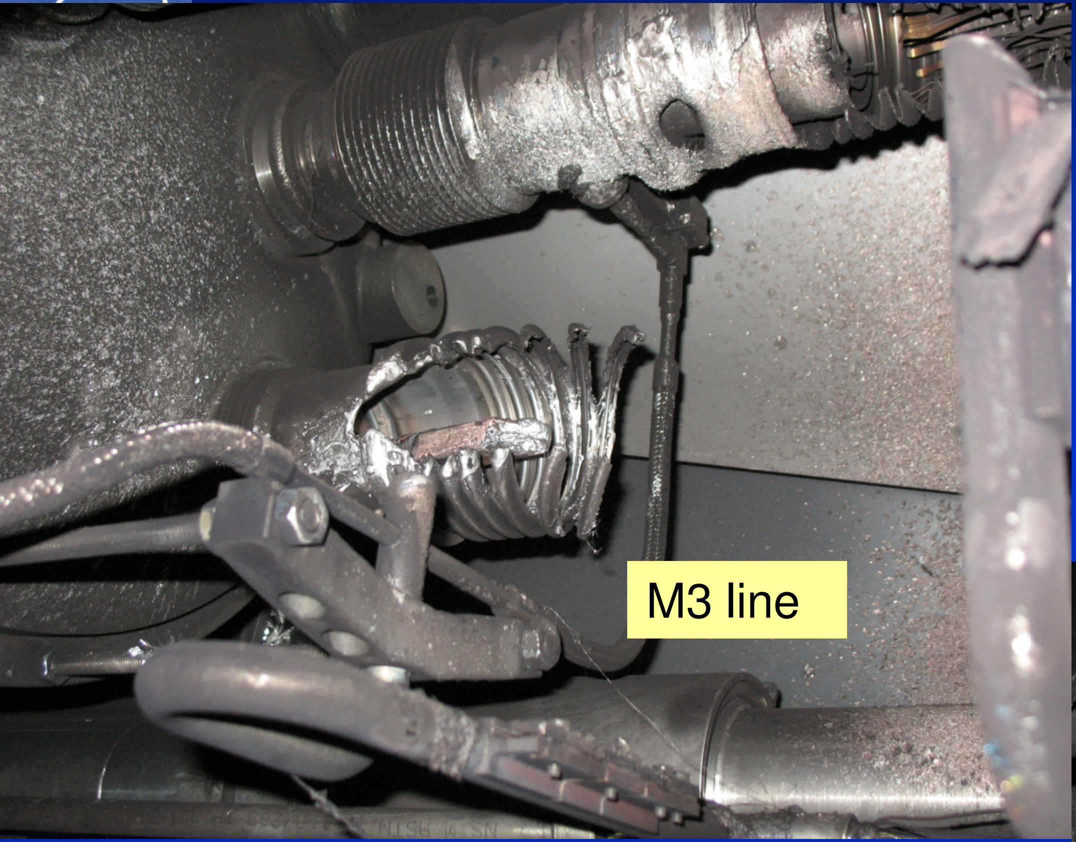
Before repair

After repair

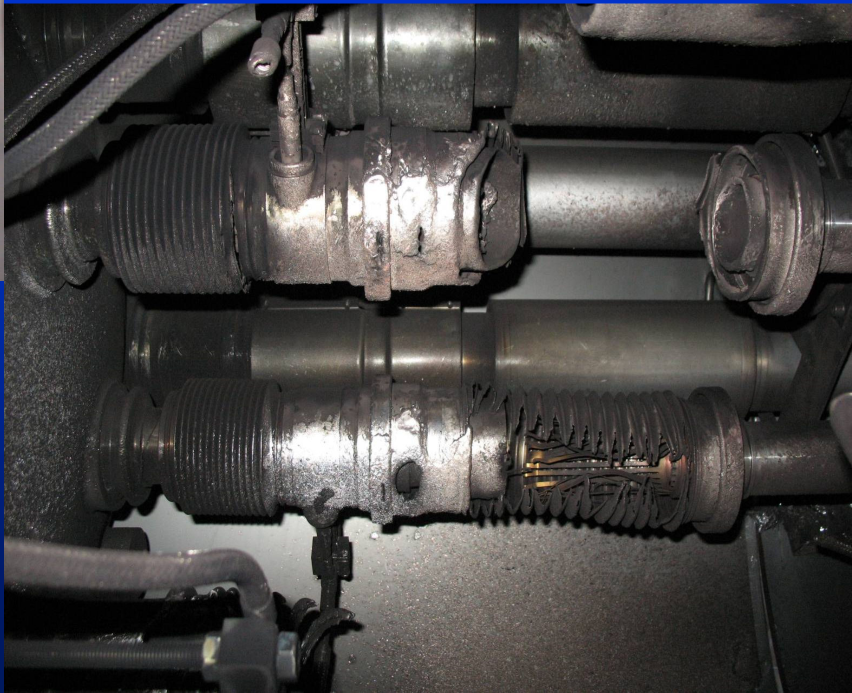
Consequences



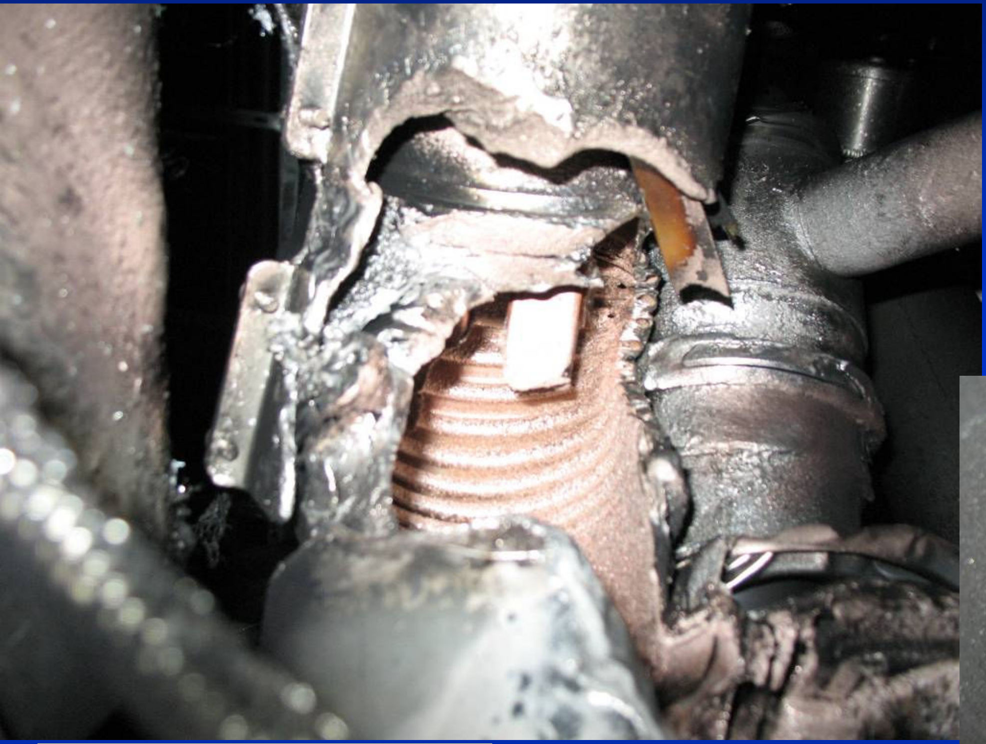
Electrical arc between C24 and Q24



V lines



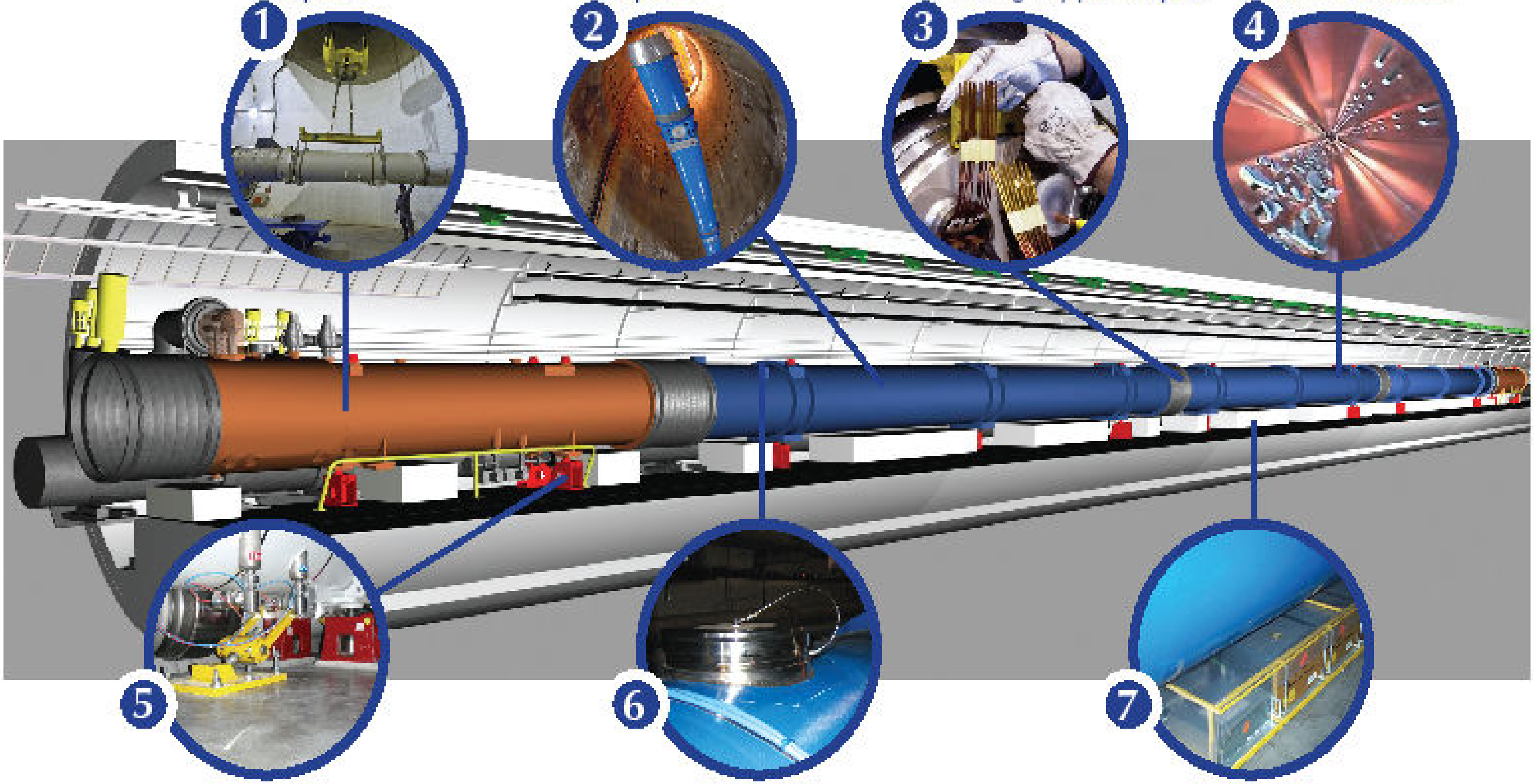
Collateral damage: secondary arcs



QQBI.27R3 M3 line

QBBI.B31R3 M3 line

The LHC repairs in detail



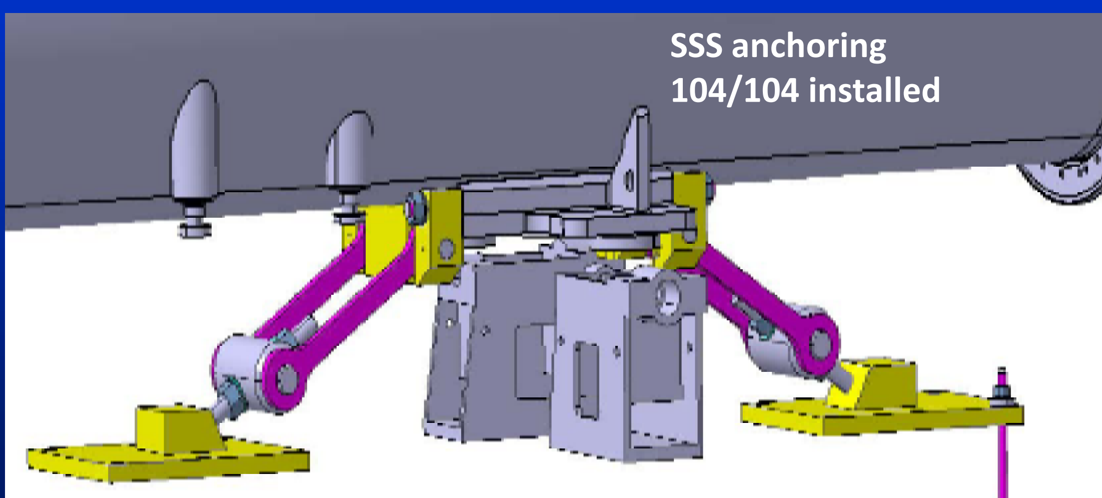
CERN

Magnet protection and anchoring

DN200 on dipoles
732/1344 installed

DN200 on ITs
24/24 installed

DN160 on SAM
92/96 installed

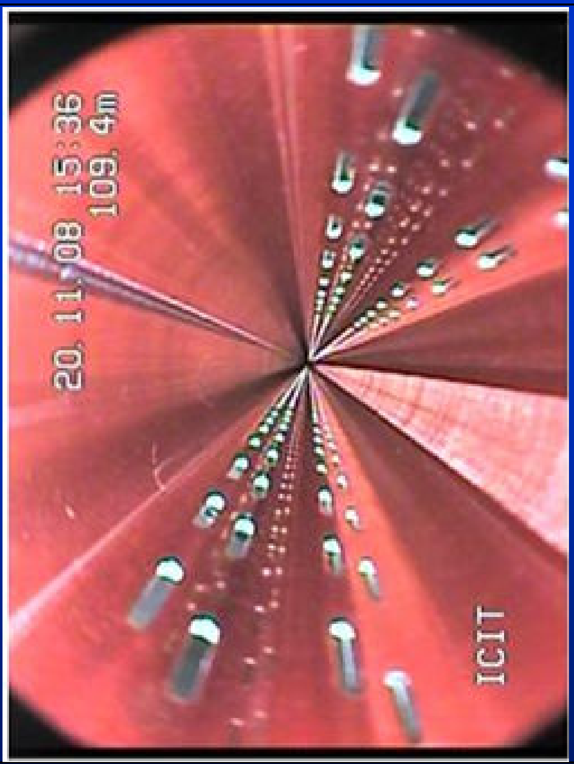
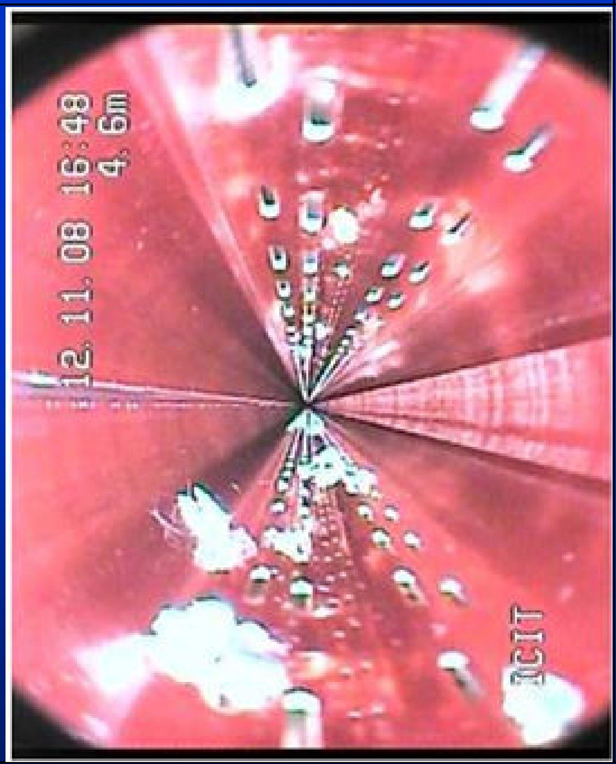
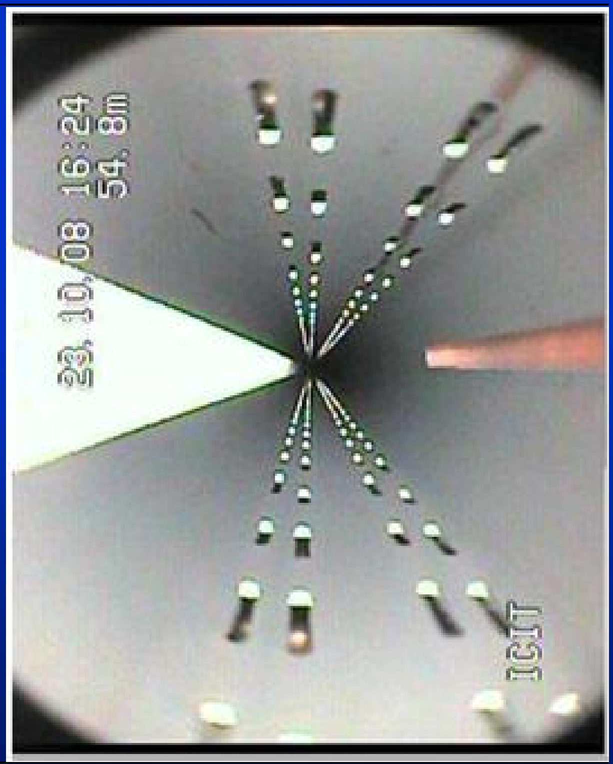


SSS anchoring
104/104 installed

DFB protection and anchoring

DSLC protection

Beam vacuum recovery in sector 3-4
Beam Vacuum Contamination

Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
		

The Large Hadron Collider

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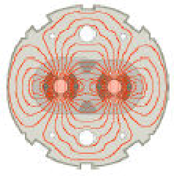
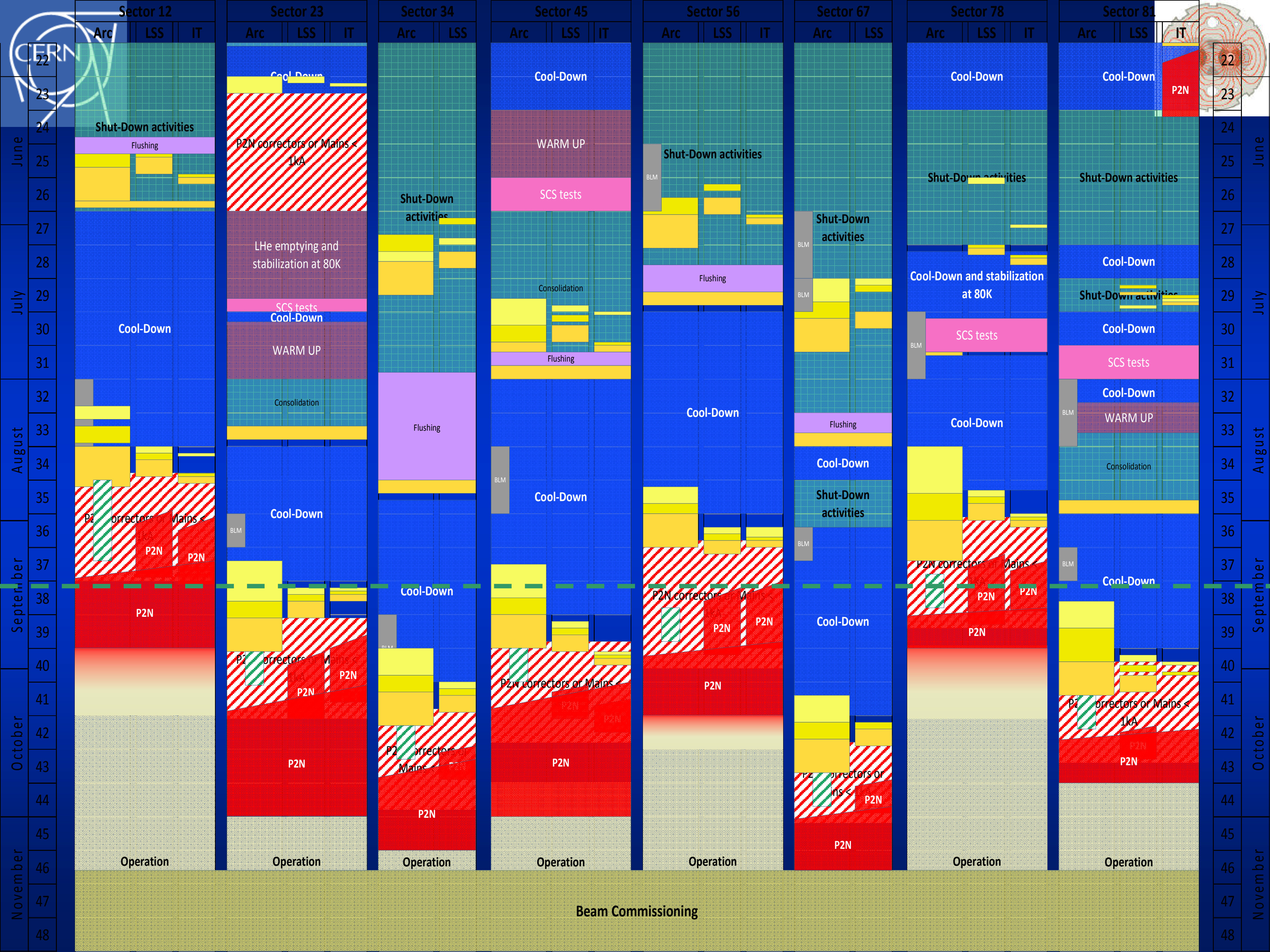
Restart in 2009



- **Restart in 2009 is determined by**
  - **Efficiency of logistics of magnets removal / installation**
  - **Efficiency of magnet repair**
  - **Efficiency of beam pipe repair / cleaning**
  - **Efficiency of interconnection activities**
  - **Time to cool down whichever sectors are warmed up**
  - **Time to re-commission all power circuits**

- **Target is beam operation in mid November of 2009**
  - **Lower energy (3.5TeV)**
  - **Lower intensity (43 to 156 bunches per beam)**

- **Push performance in 2010**



Sector 12
Sector 23
Sector 34
Sector 45
Sector 56
Sector 67
Sector 78
Sector 81
Arc
LSS
IT
June
July
August
September
October
November
22
23
24
25
26
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44
45
46
47
48
Shut-Down activities
Flushing
Cool-Down
P2N correctors or Mains < 1kA
P2N
Operation
LHe emptying and stabilization at 80K
SCS tests
WARM UP
Consolidation
BLM
Cool-Down and stabilization at 80K
Beam Commissioning

Thank you for your attention

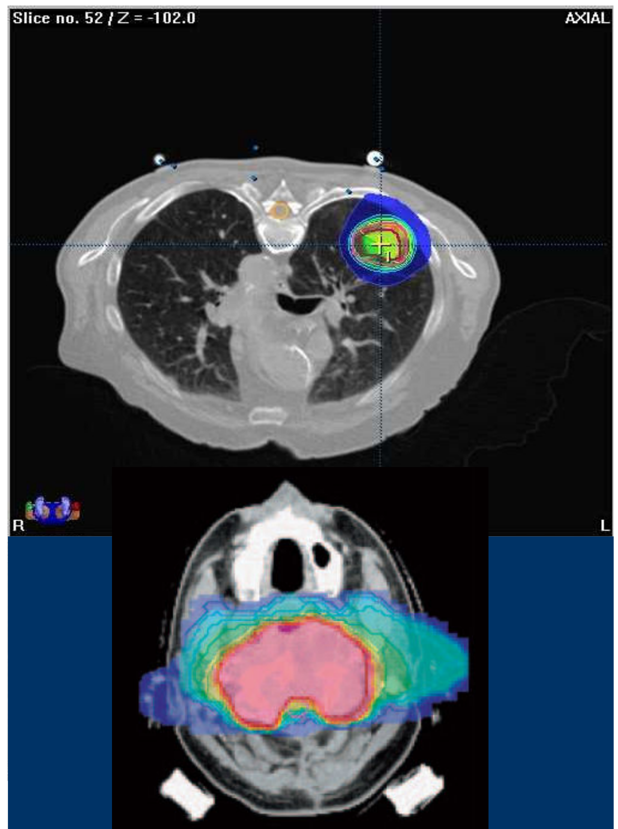
questions?

SPARE SLIDES

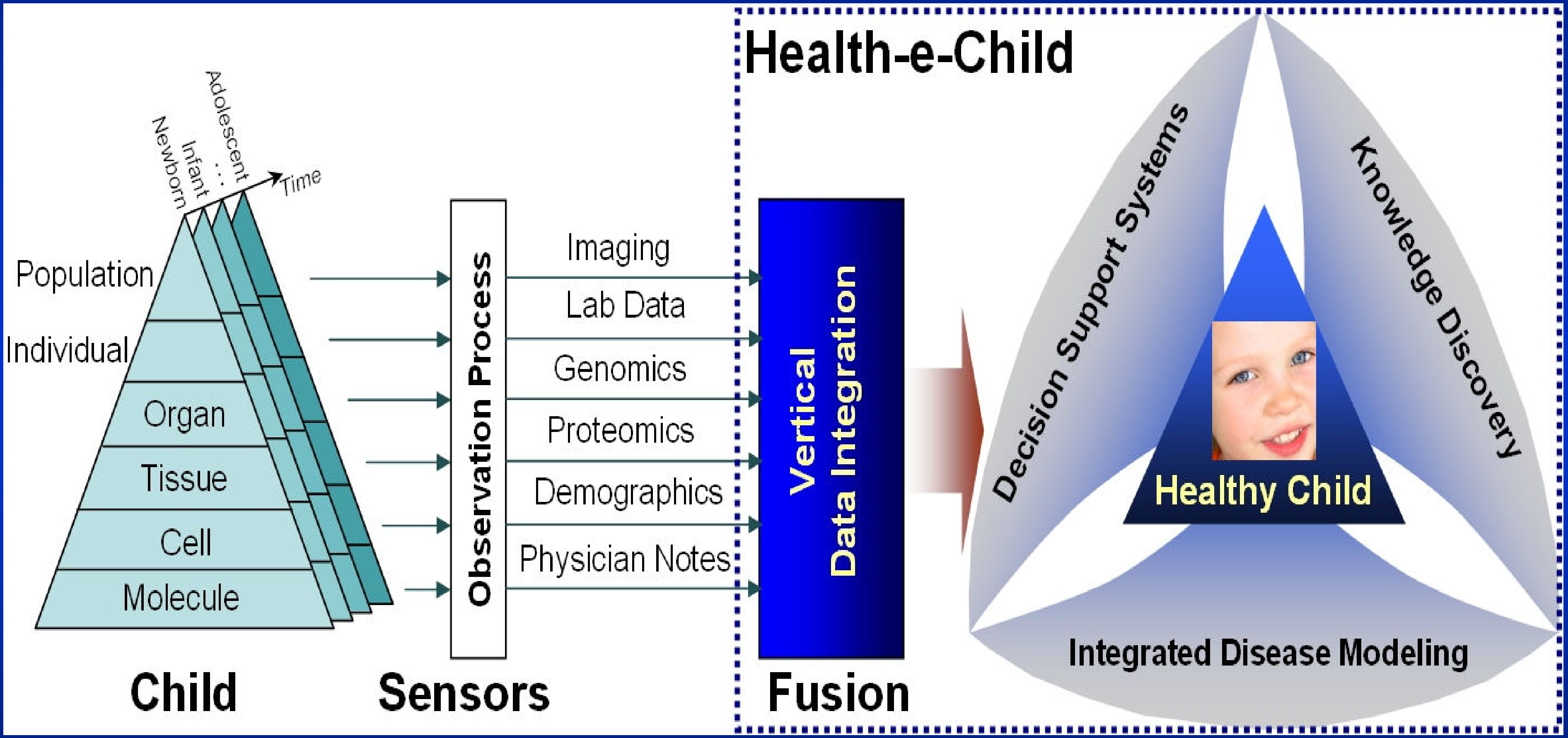
Challenge

Make appropriate use of medical imaging, treatment planning and other clinical data for the best cure

- Treatment Planning
- Realization



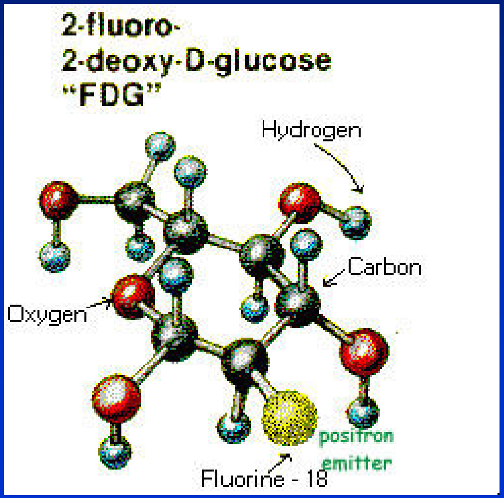
Health-e-Child on a slide

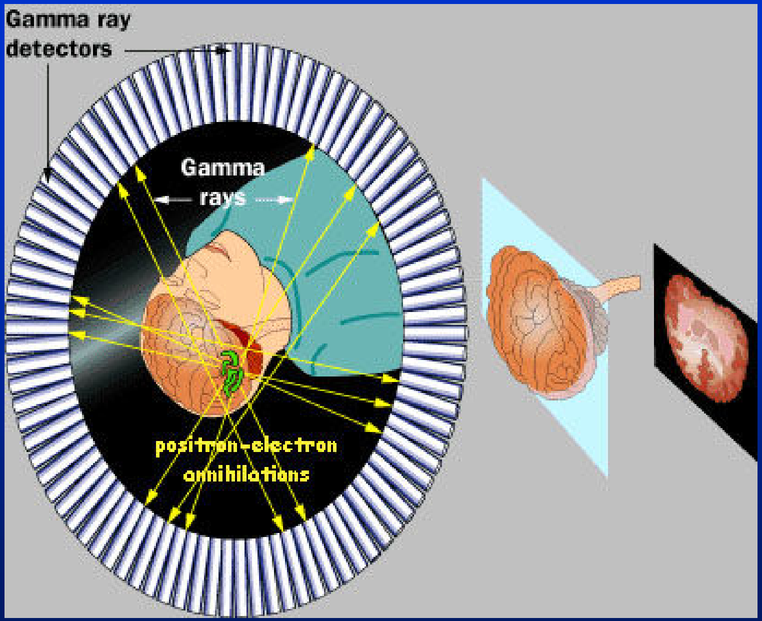


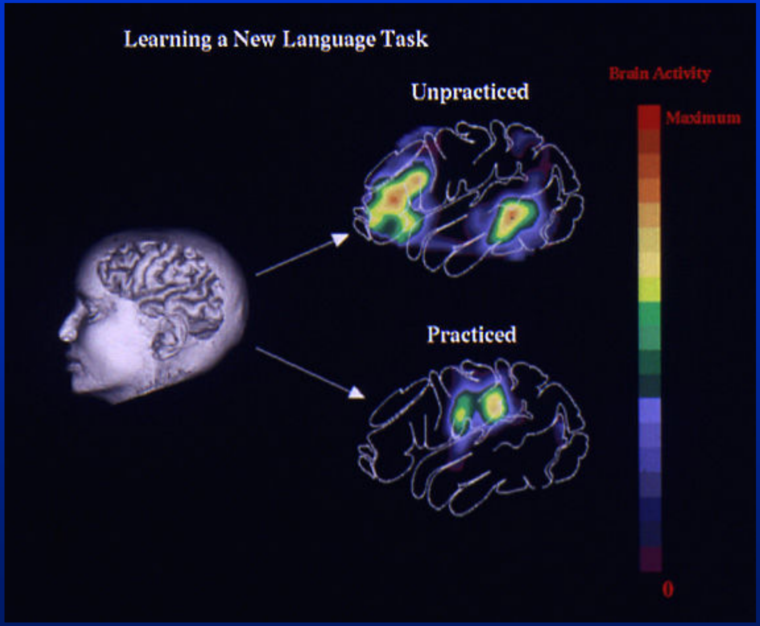
Antimatter application: Positron Emission Tomography

$^{18}F \rightarrow ^{18}O + e^{+} + \text{neutrino}$

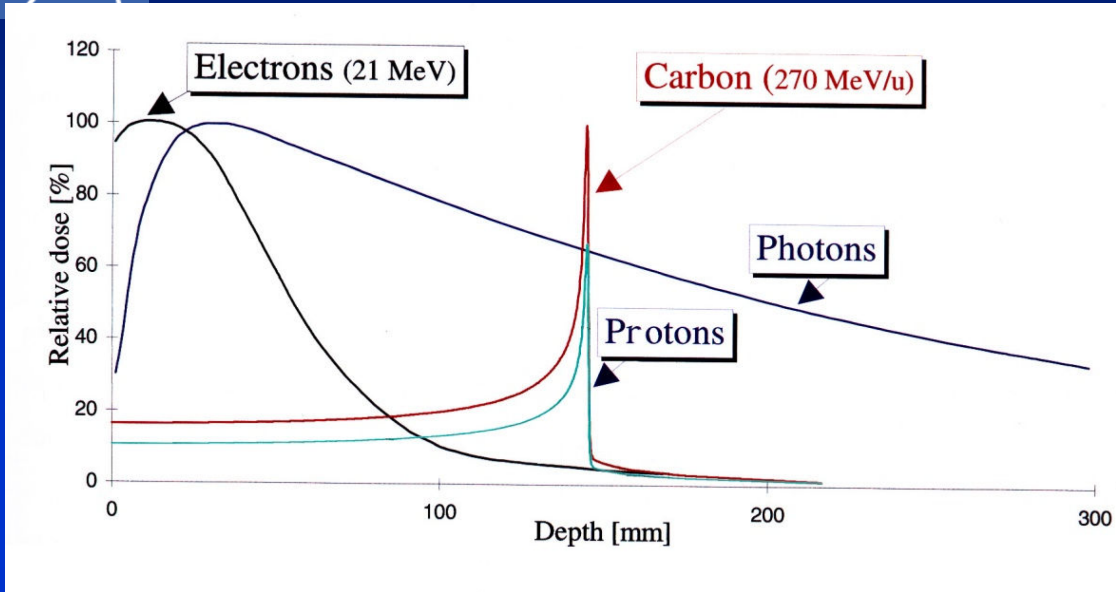
$e^{+} + e^{-} \rightarrow 2\ \text{photons}$







Hadrontherapy vs. radiotherapy



- Tumours close to critical organs
- Tumours in children
- Radio-resistant tumours

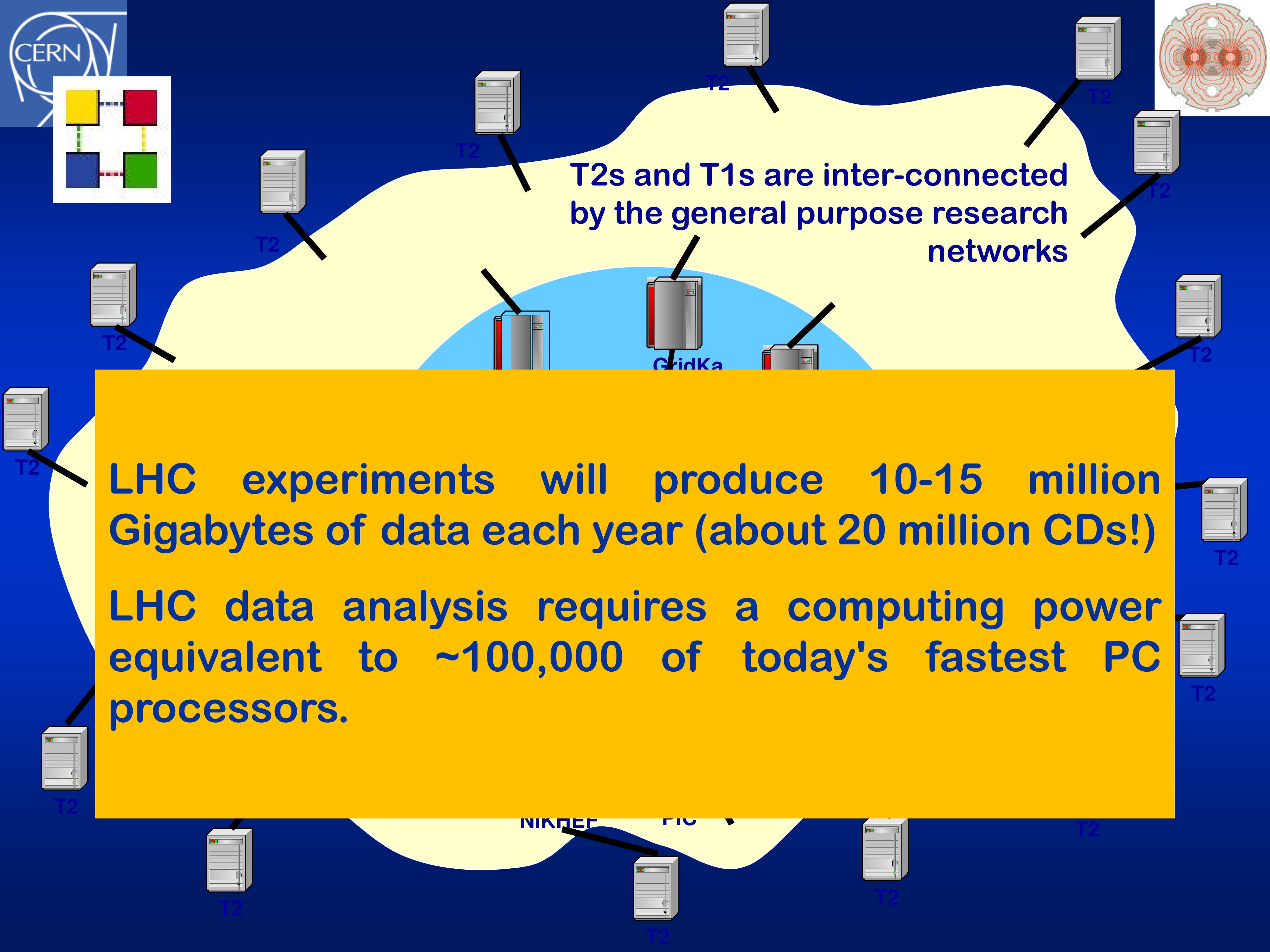
Photons and Electrons vs. Hadrons

Photons and Electrons

- Physical dose high near surface
- DNA damage easily repaired
- Biological effect lower
- Need presence of oxygen
- Effect not localised

Hadrons

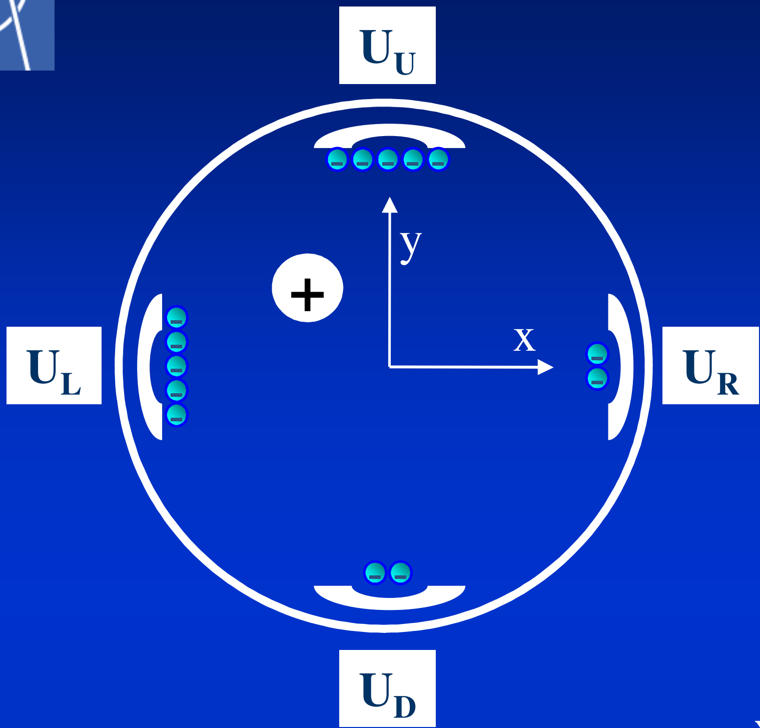
- Dose highest at Bragg Peak
- DNA damage not repaired
- Biological effect high
- Do not need oxygen
- Effect is localised



LHC experiments will produce 10-15 million Gigabytes of data each year (about 20 million CDs!)

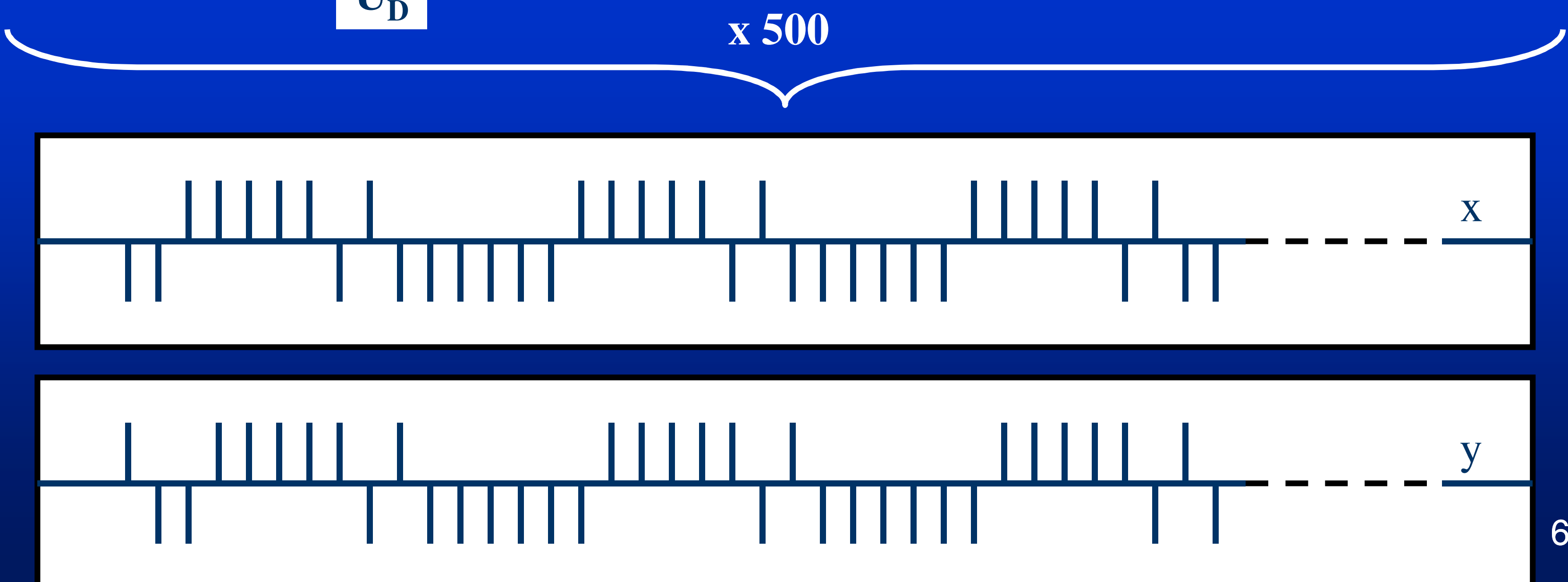
LHC data analysis requires a computing power equivalent to ~100,000 of today's fastest PC processors.

Beam position monitors



$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta}{\Sigma}$$

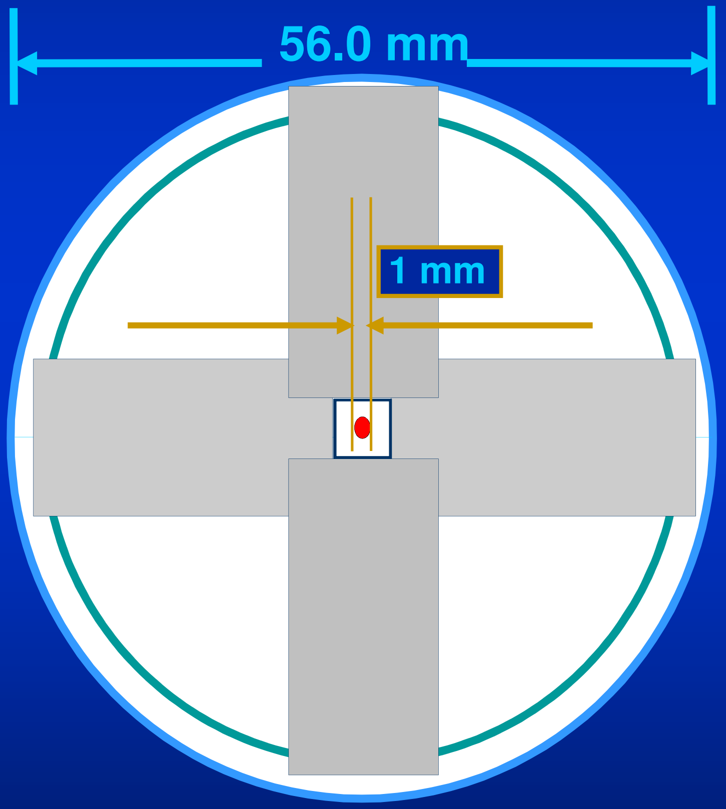
$$y \propto \frac{U_U - U_D}{U_U + U_D} = \frac{\Delta}{\Sigma}$$

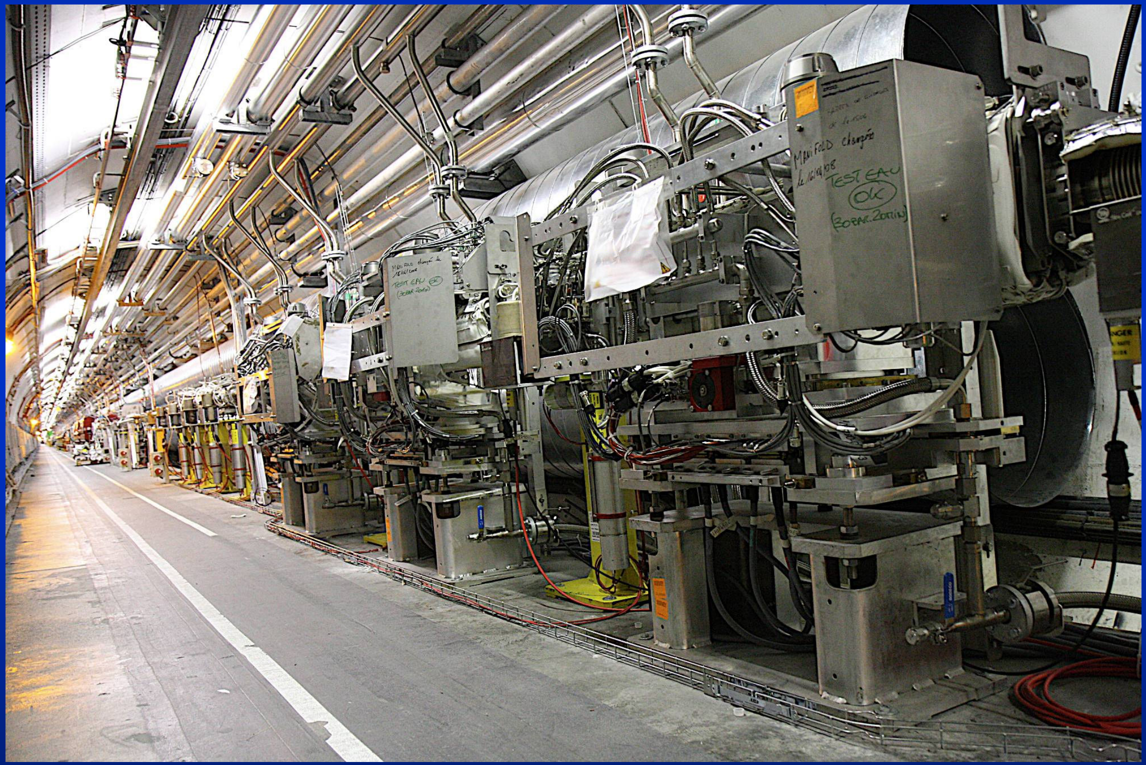



ROCLA
ROBOTRUCK
RISK OF
LIQUID
AIR

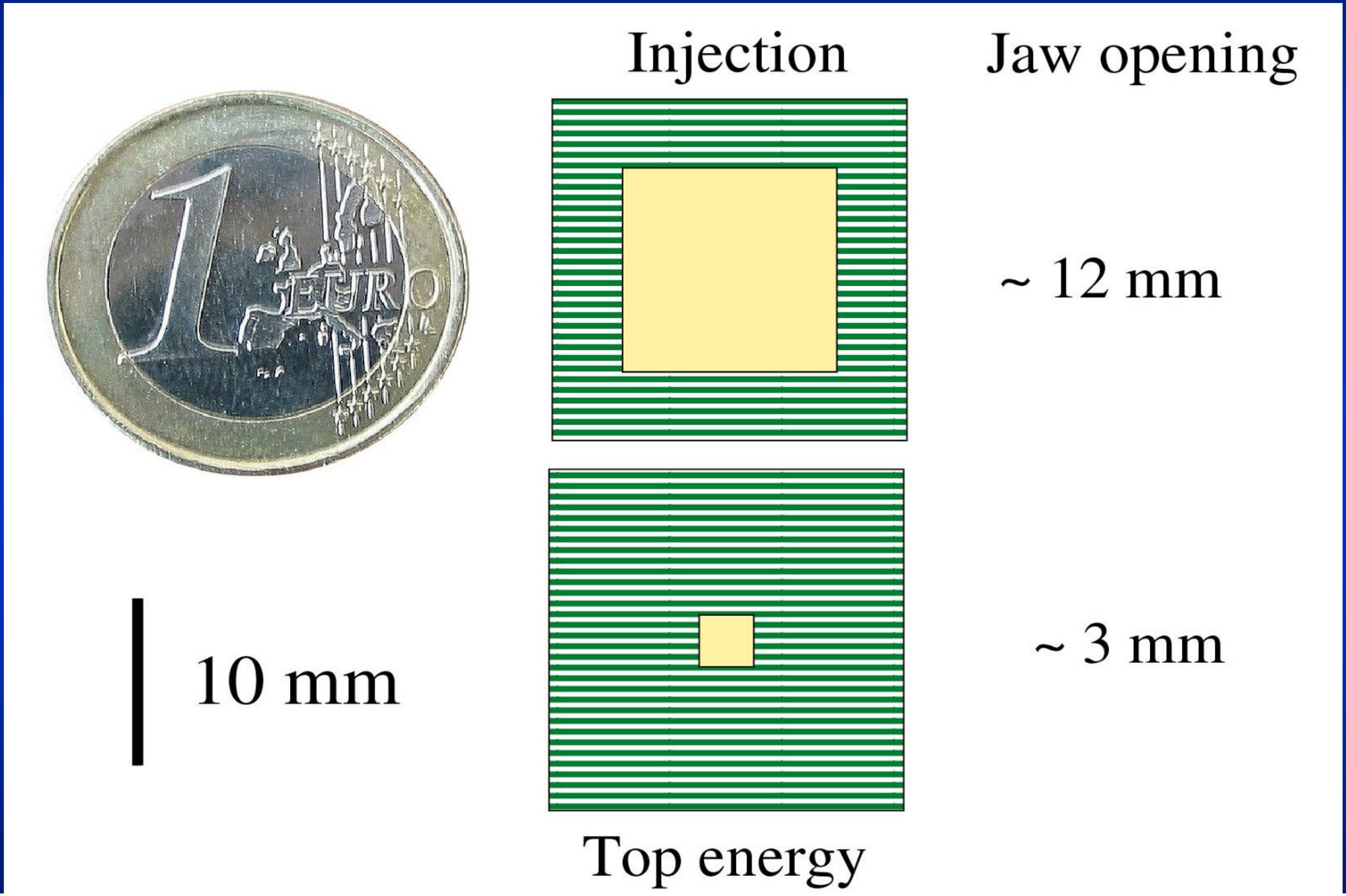
Collimators (points 3 and 7)

- **Intercept particles that have strayed outside acceptable limits**





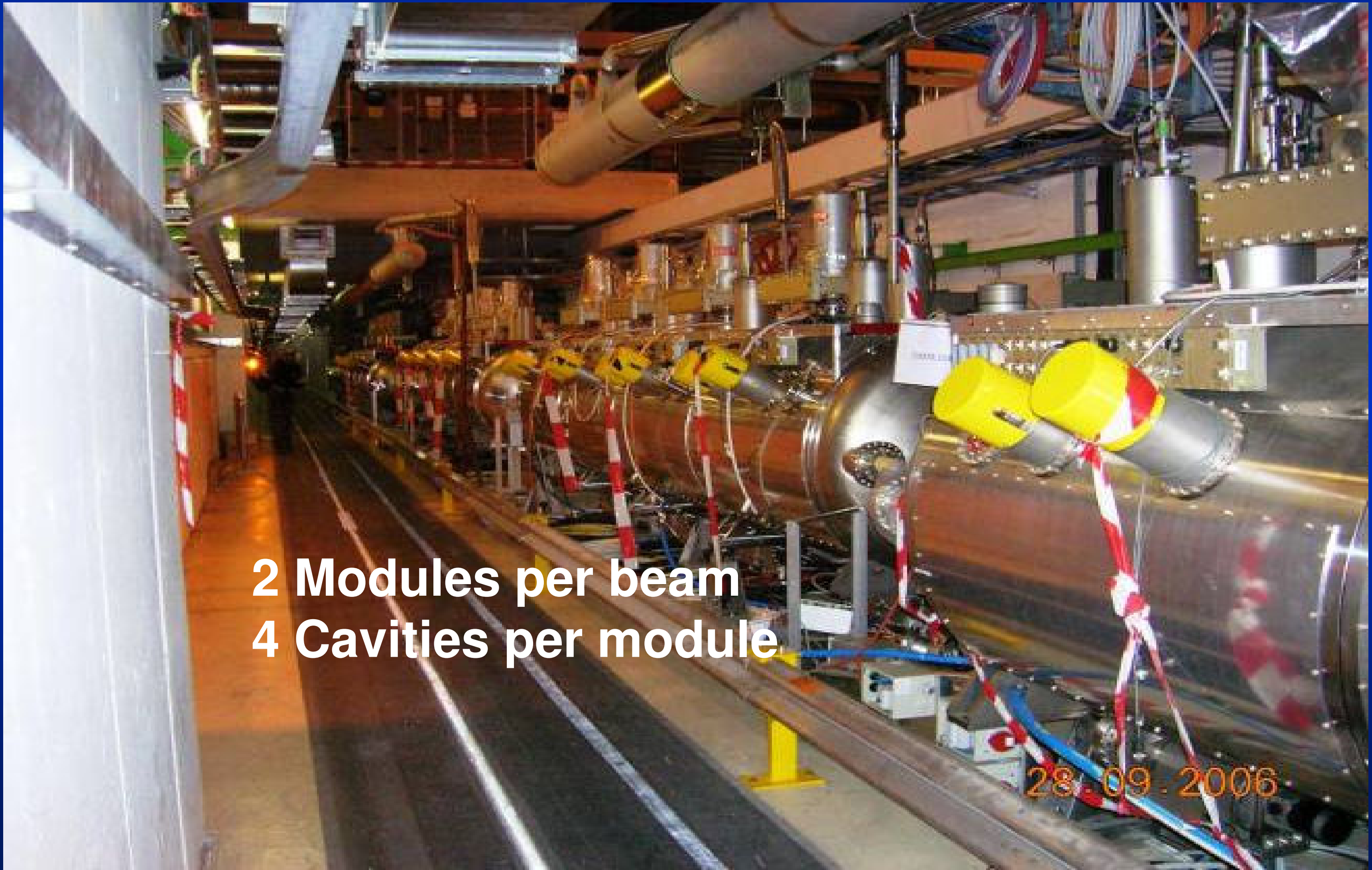
Collimating with small gaps



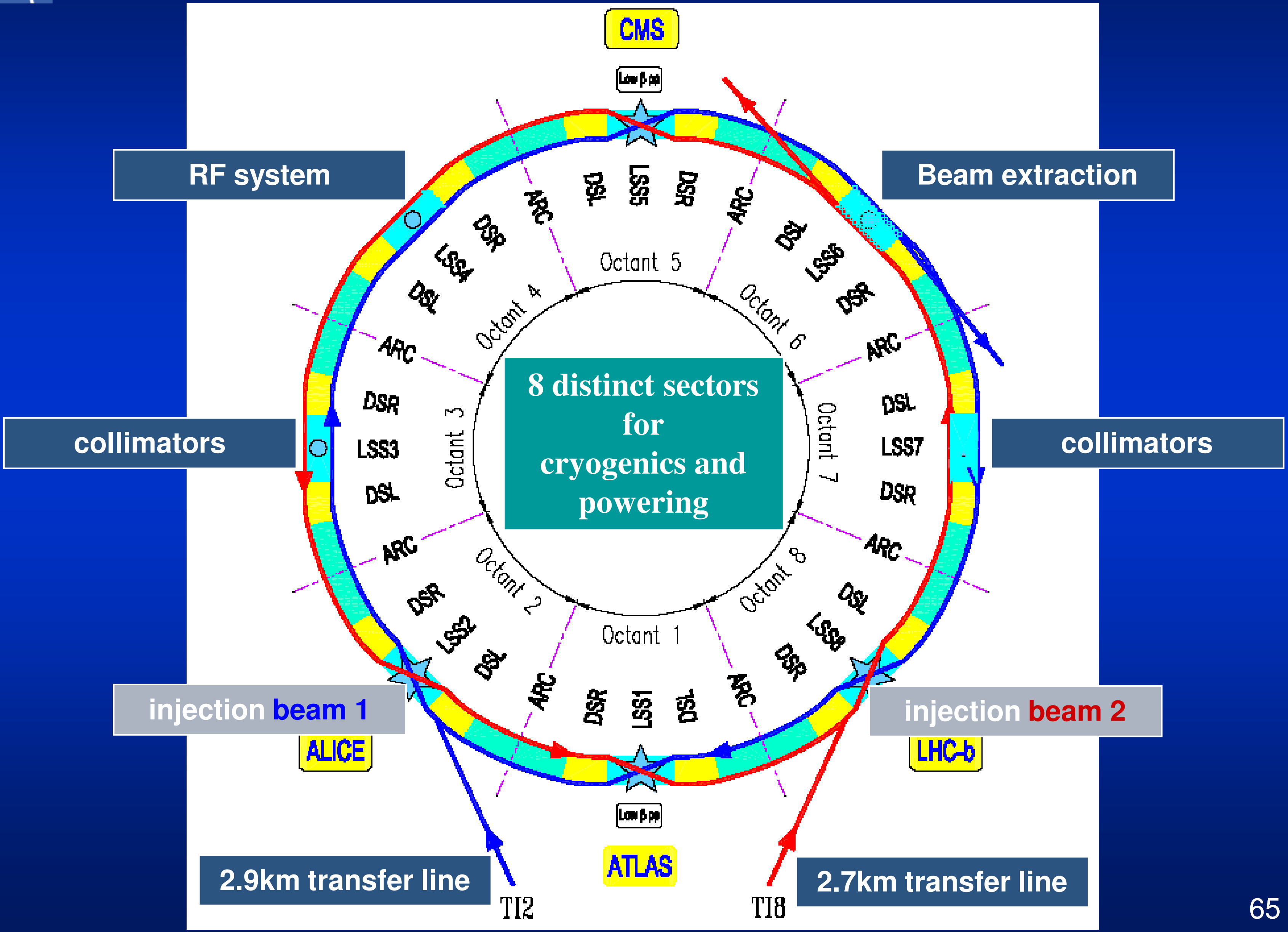
LHC beam will be physically quite close to collimator material and collimators are long (up to 1.2 m)!

Super conducting RF systems (point 4)

- Give energy to the particles as they pass through



Schematic of the LHC



Safety Study

Likelihood for any unacceptable failure

Case studied	Unsafety/year	False dumps/year
Default scenario	2.41×10^{-7} (> SIL4)	4.06
No redundant power triggers	2.34×10^{-6} (SIL4)	3.02
No redundant triggering sys.	4.68×10^{-4} (SIL2)	4.02
14 MKD	0.011 (SIL1)	3.89
No BETS	0.059 (< SIL1)	3.40
No RTS	0.32 (< SIL1)	4.06

All these systems are obligatory !

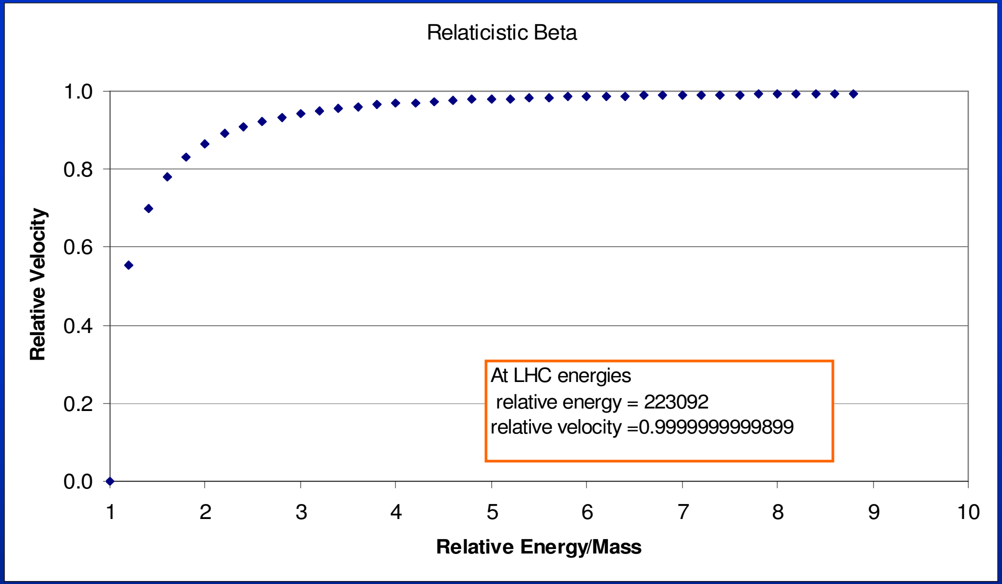
When one accelerates a particle…

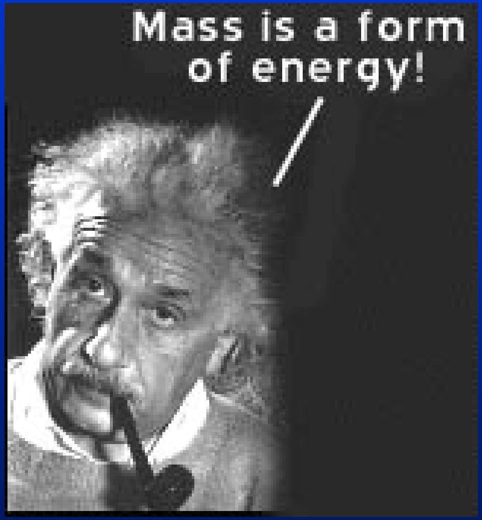
It does not necessarily go much faster

Its mass increases

$$E = m c^2$$

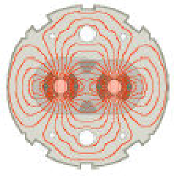
In an interaction, it can transform its energy into massive particles





one transforms energy into mass

Galileo and Rutherford



- Galileo, "measure what is measureable and make measureable what is not"
- Lord Rutherford was the "god-father" of accelerators since he challenged future generations of accelerator builders to invent reliable machines which could accelerate particles to higher and higher energies. In his inaugural presidential address to the Royal Society in London in 1928, he said "I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances". This was the start of a long quest for the production of high energy beams of particles in a very controlled way.
- Particle accelerators of today are among the most complicated and expensive scientific instruments ever built by mankind and they exploit every aspect of today's cutting edge technologies. In many cases accelerator needs have been the driving force behind these new technologies; necessity being the mother of invention.

- Particle accelerators are also used in many different applications such as material analysis and modification and spectrometry especially in environmental science.
- About half of the world's 15,000 accelerators are used as ion implanters, for surface modification and for sterilization and polymerization.
- The ionization arising when charged particles are stopped in matter is often utilized for example in radiation surgery and therapy of cancer. At hospitals about 5,000 electron accelerators are used for this purpose. Accelerators also produce radioactive elements that are used as tracers in medicine, biology and material science.
- In material science, ion and electron accelerators are used to produce neutrons and photons over a wide range of energies. Well-defined beams of photons are for example increasingly used for lithography in order to fabricate the very small structures required in electronics.

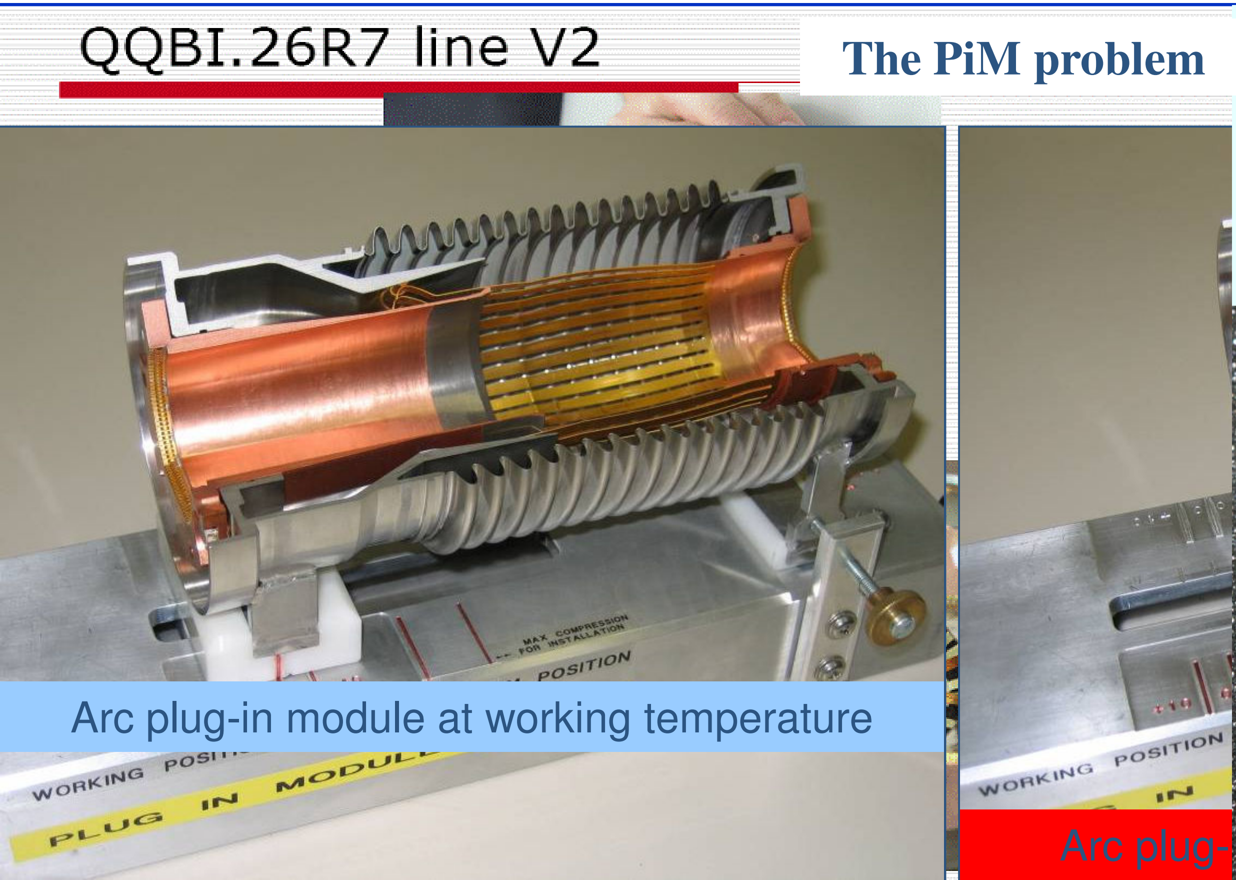
Construction and commissioning 2002-2008

Tunnel activity determined by

Triplet (2007)

2002	2003	2004	2005	2006	2007	2008

The PiM problem

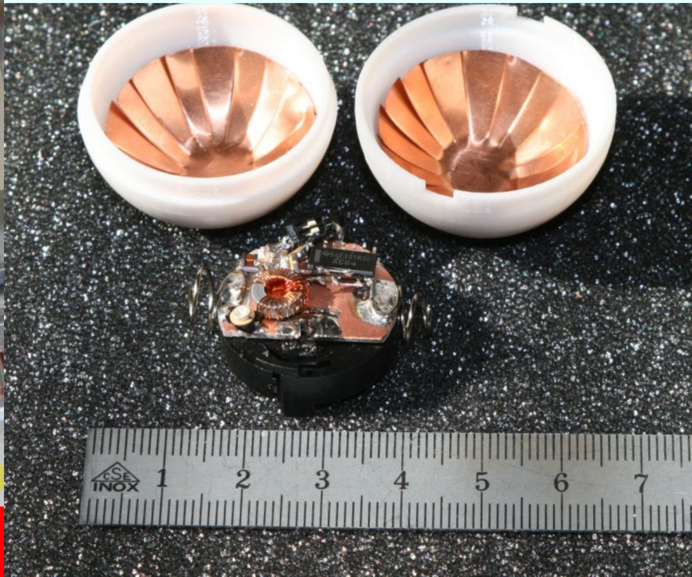


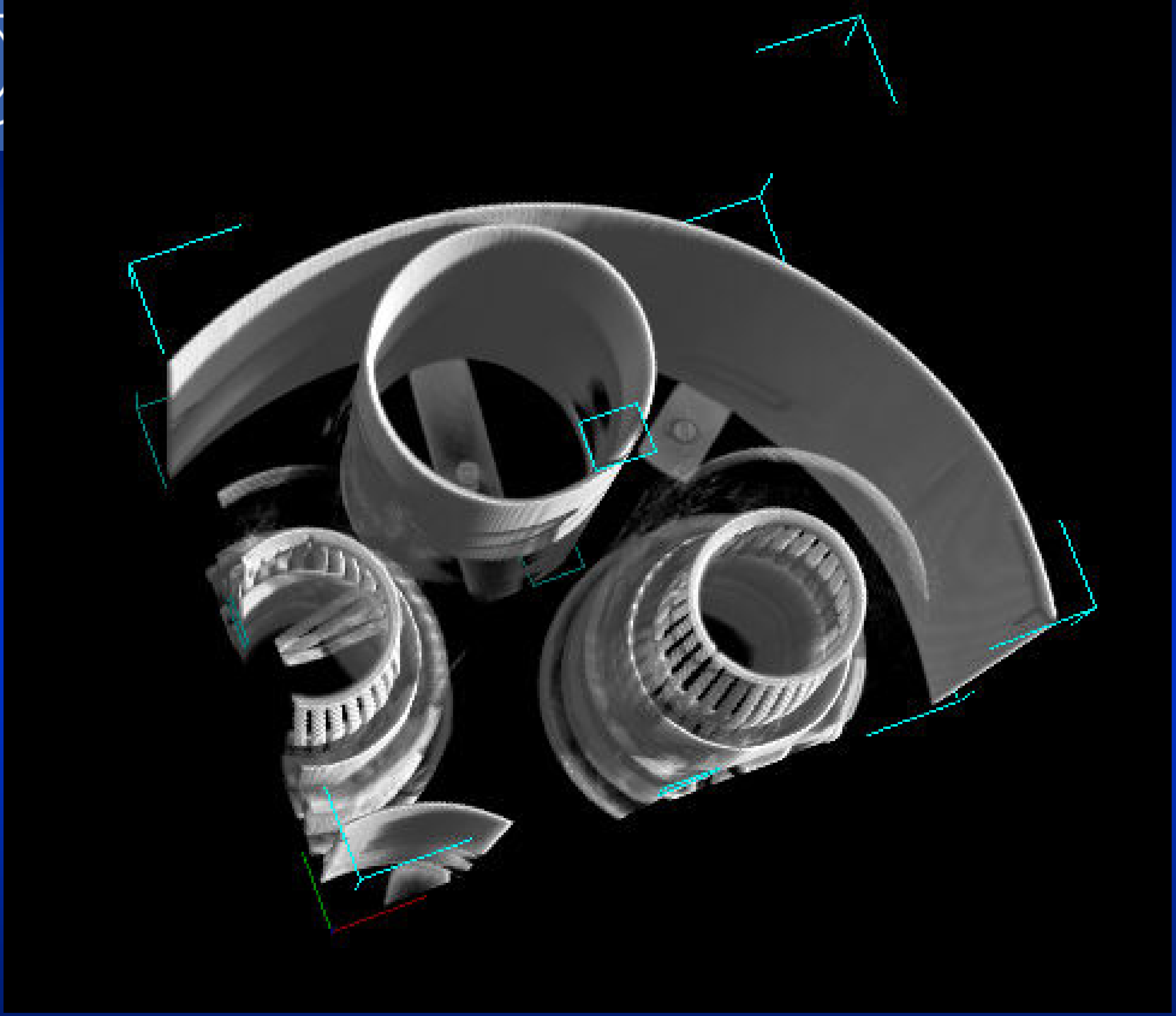
Arc plug-in module at working temperature

-- Innovation --

Light ball transmitting at 40MHz
Blown through an LHC arc
Detected by Beam Position Monitors

Stopped by buckled PiMs

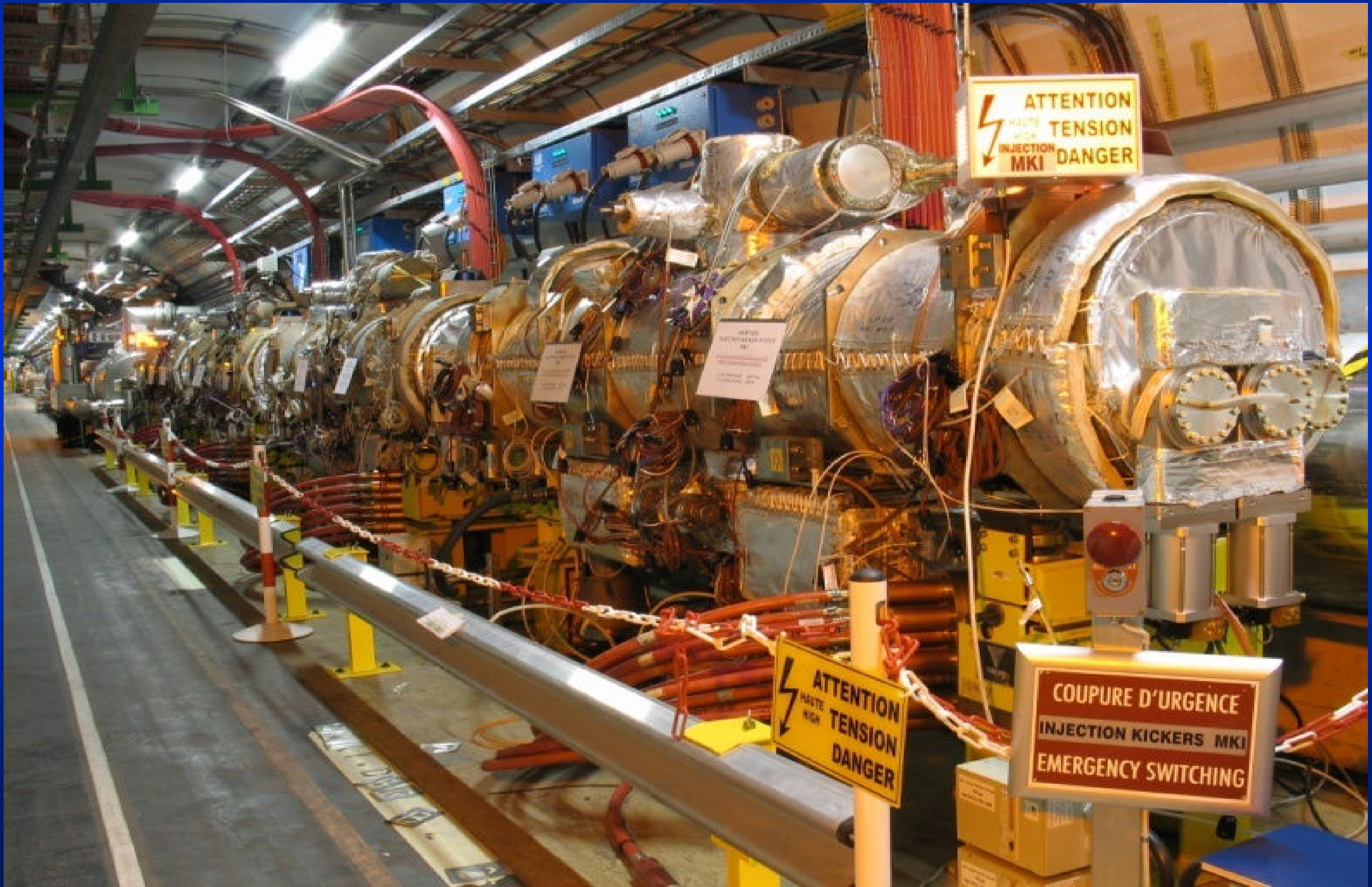




New 3D X-Ray technique

Injection systems (points 2 and 8)

- Deflect the incoming particles onto the axis of the LHC

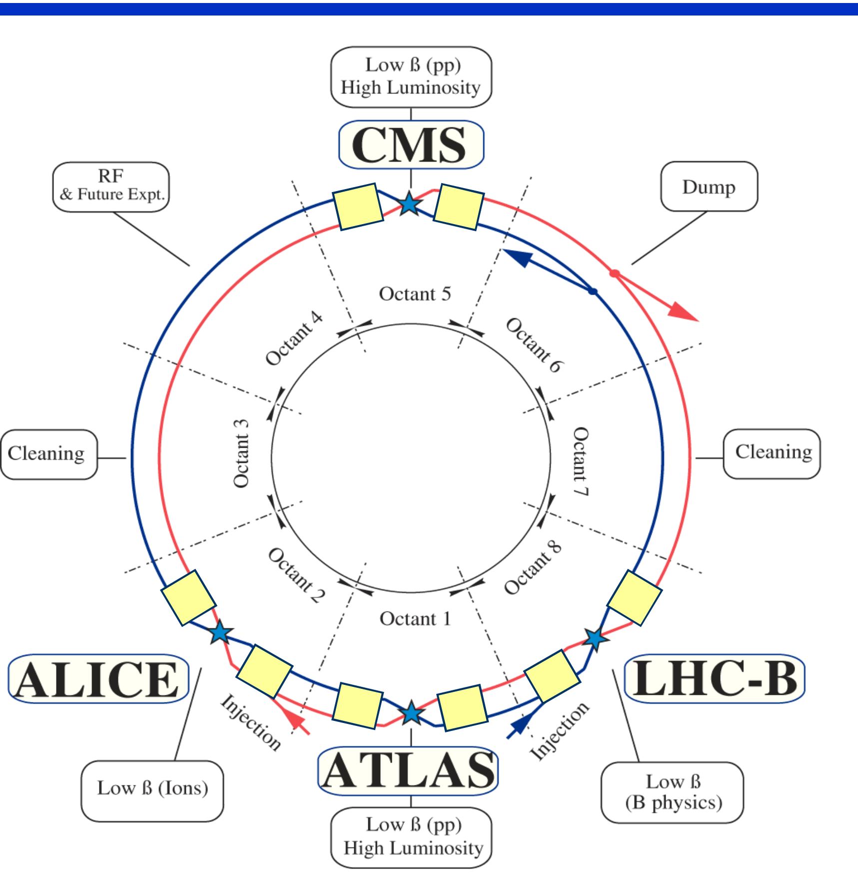


Construction and commissioning 2002-2008

Tunnel activity determined by

Triplet (2007)

2002	2003	2004	2005	2006	2007	2008



Inner Triplets
Either side of each experiment
Provide focusing at the Interaction Point
Three superconducting magnet assemblies

Construction and commissioning 2002-2008

Tunnel activity determined by

LEP →

2002	2003	2004	2005	2006	2007	2008





Construction and commissioning 2002-2008

Tunnel activity determined by

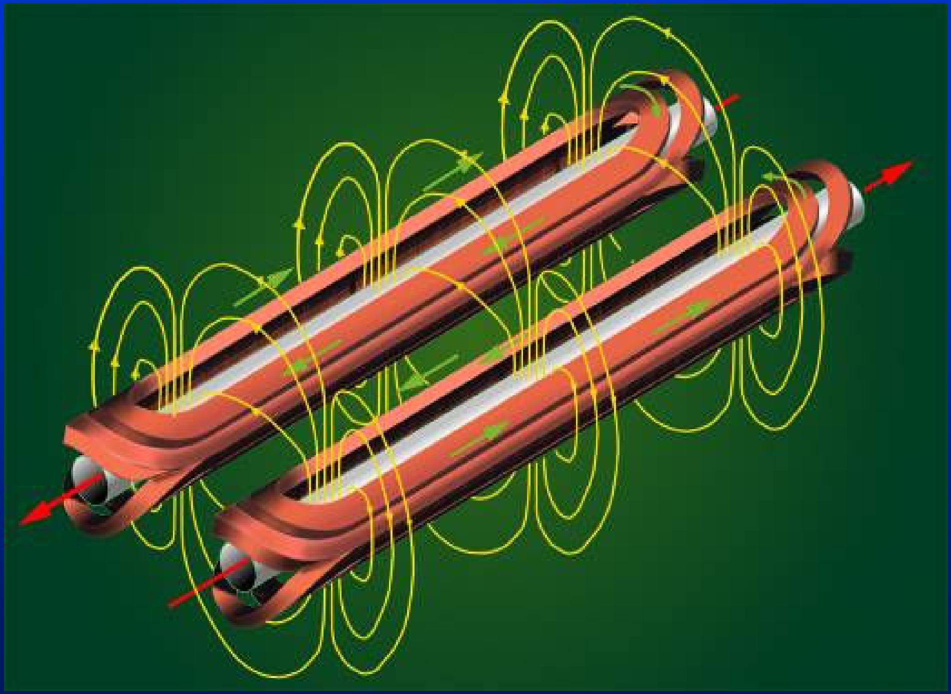
Helium Distribution Line

2002	2003	2004	2005	2006	2007	2008

Big industrial system: 27km of helium distribution lines installed by supplier
Initially problems with geometry, weld quality, procedures, leaks, support tables

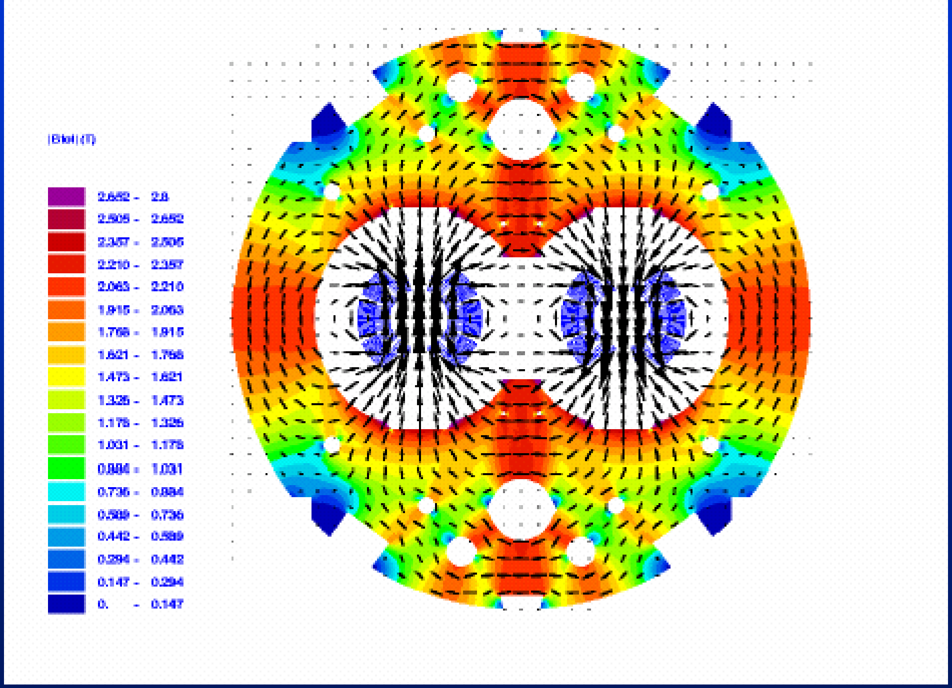
LHC design parameters

- **Luminosity (defines rate of doing physics)** **10^{34} cm^{-2} s^{-1}**
  - **Excludes proton – antiproton machine (Tevatron, SPPbarS)**
  - **Hence proton – proton machine**
  - **Separate bending fields and vacuum chambers in the arcs**

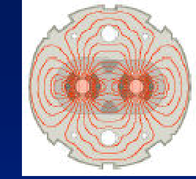


LHC design parameters

- **Energy 7TeV per beam ⇔ Dipole field 8.33Tesla**
  - **Superconducting technology needed to get such high fields**
  - **Tunnel cross section (4m) excludes 2 separate rings (RHIC)**
  - **Hence twin aperture magnets in the arcs**



Post Mortem (needles and haystacks)



- Following the incident, a close look at the logged cryogenic data (temperatures and valve states) indicated **abnormal behaviour** in the cell that was at the origin of the fault

mK

- This was followed by systematic scrutiny of all data logged during the weeks of power testing of all 8 sectors
- **Anomalous cryogenic behaviour** found in sector 12 at 7kA
  - Higher than nominal **heat load** in cryogenic sector 15 R1

W

- Confirmed by detailed tests in late 2008
- Corresponding **electrical resistance** calculated

90nΩ

!

- **No other faulty splice has been found**

0.3nΩ!

- Electrical measurements located it to **inside** a dipole

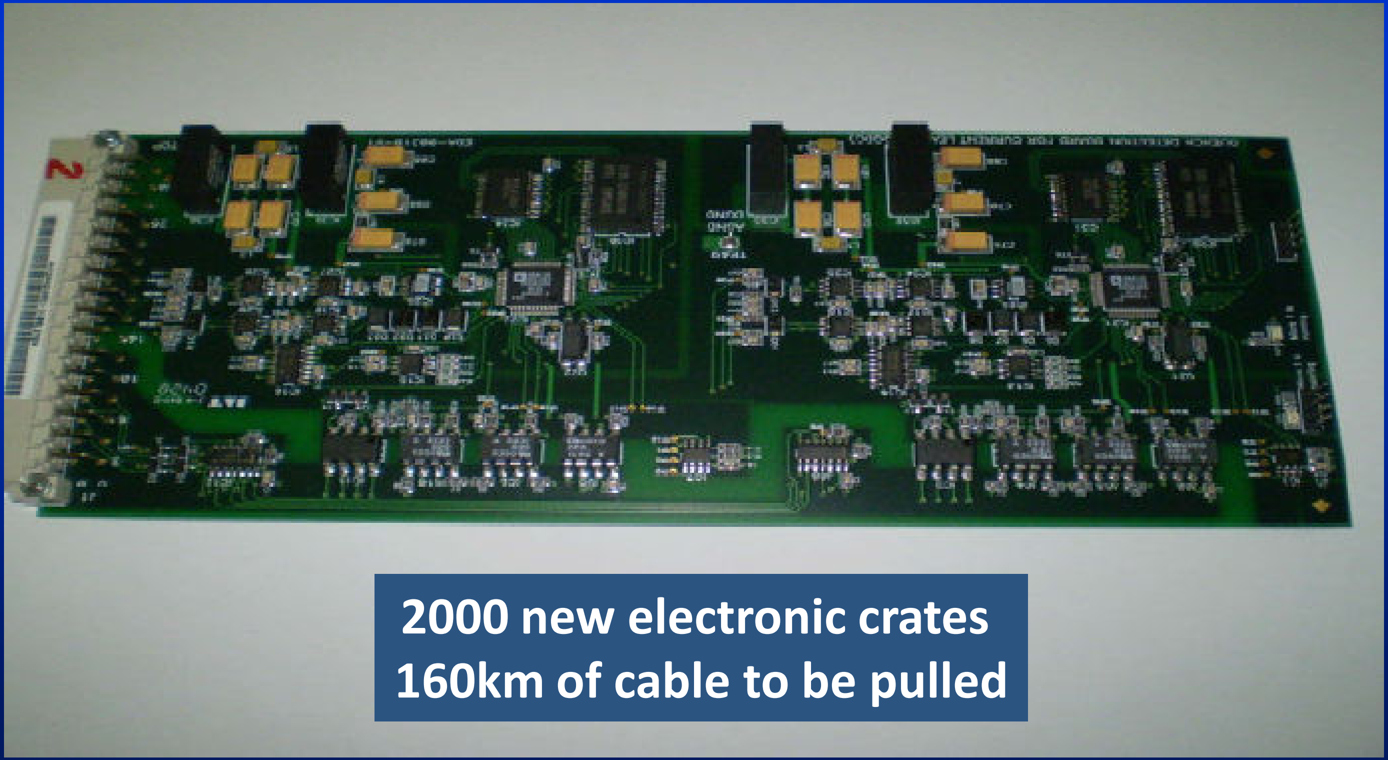
100nΩ

- Another resistance found **inside** a dipole in sector 67

47nΩ

Protection

- These investigations have led to the development of **powerful calorimetric and electric methods** to detect excessive resistances in the main LHC magnet circuits
- These methods have been prototyped and will be further improved before being installed machine-wide and applied as **dedicated procedures** during the machine commissioning



2000 new electronic crates
160km of cable to be pulled

Further measures

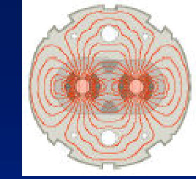
- **Mitigate the consequences of any event similar to that in sector 34 by increasing the helium gas release capability**

- **All quadrupole cryostats have spare flanges**
  - **Equip them with new full-flow release valves**
  - **Gives Factor 8 in discharge cross section**
  - **Can and will be done *in situ* at cold**

- **Addition of full-flow release valves on EVERY dipole cryostat (all 1232)**
  - **Brings overall discharge cross section increase to Factor 40**
  - **Can only be done at warm**

Present major activity foreseen in the different sectors	
Sector	**Activity**
34	Repair of magnets and beam pipes
56	Warmed up for repair of known non-conformity
12	Warmed up for exchange of dipole B16.R1
67	Warmed up for exchange of dipole B32.R6
Others	Kept cold

LHC timeline



1982 : First studies for the LHC project

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction *(7TeV machine)*

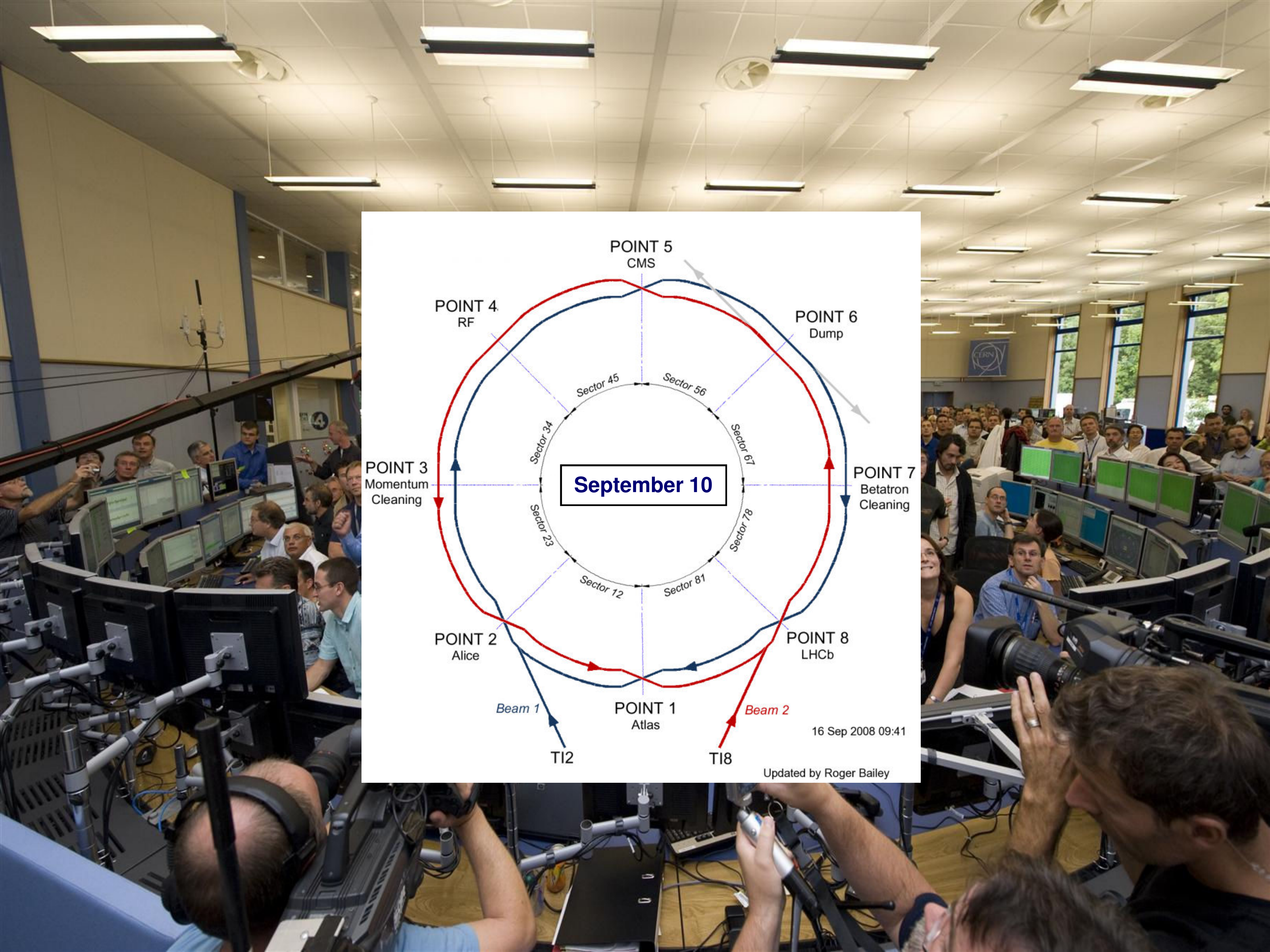
2003 : Start of the LHC installation

2006 : Start of hardware commissioning

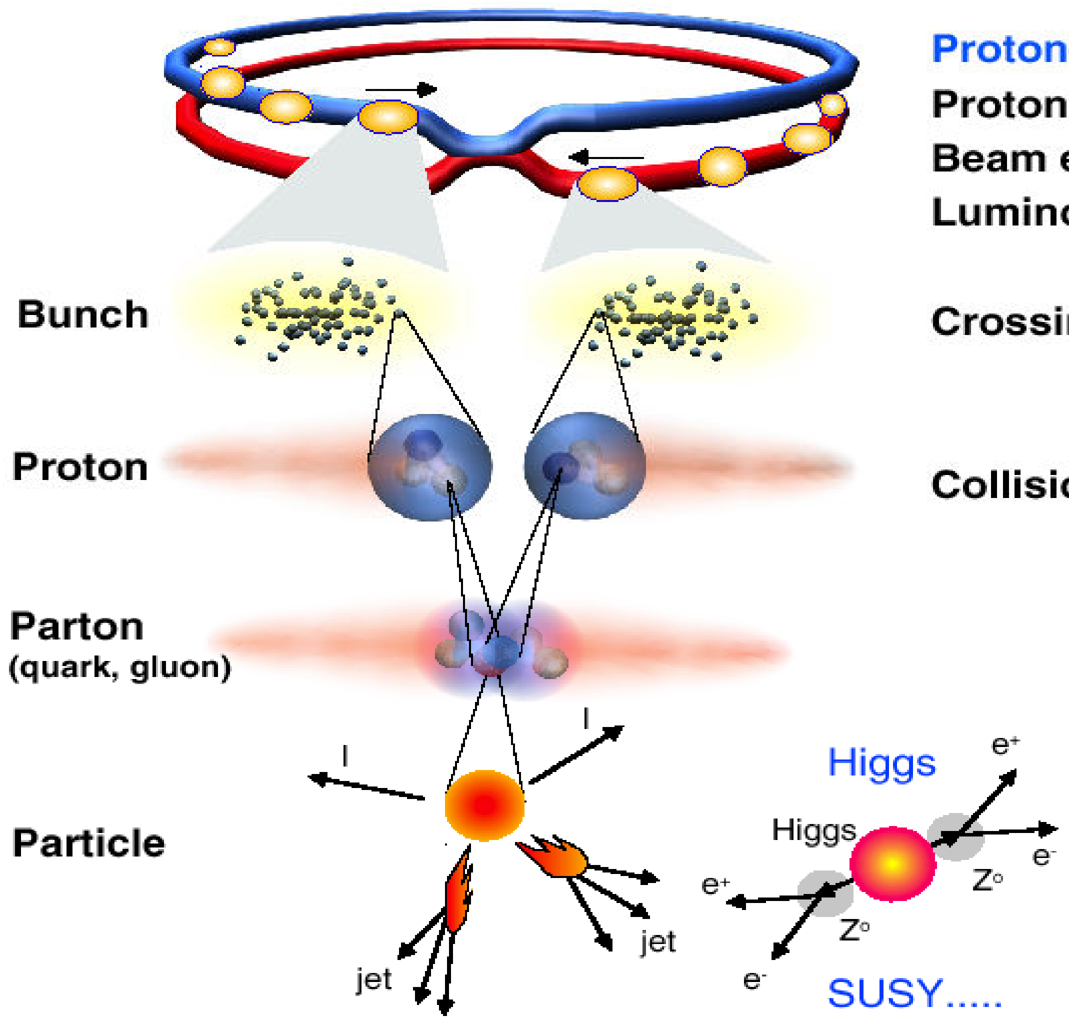
2007 : End of installation and start of cool-down

2008 : Start of beam commissioning

- 1984 : Start of LEP construction
- 1989 : Start of LEP operation
- 1995 : Start of LHC experiment civil engineering
- 2000 : End of LEP operation


POINT 5
CMS
POINT 4
RF
POINT 6
Dump
Sector 45
Sector 56
Sector 34
Sector 67
POINT 3
Momentum
Cleaning
September 10
POINT 7
Betatron
Cleaning
Sector 23
Sector 78
Sector 12
Sector 81
POINT 2
Alice
POINT 8
LHCb
Beam 1
POINT 1
Atlas
Beam 2
16 Sep 2008 09:41
TI2
TI8
Updated by Roger Bailey

Collisions at LHC



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Selection of 1 in 10,000,000,000,000

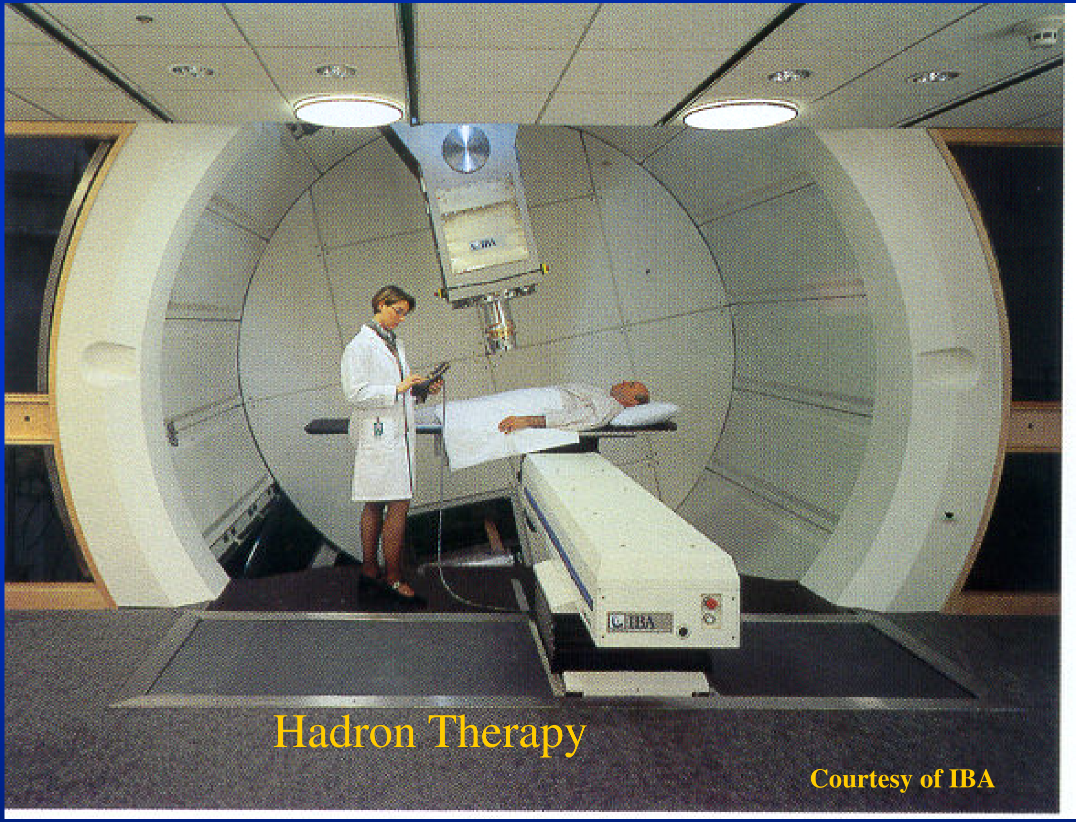
Some different probe particles and their ability to resolve objects of small dimensions. Typical values for kinetic energies and wavelengths are given in the units electron volt (eV) and pico-meter (pm) respectively. In principle, objects can be resolved if they are larger than one wavelength of the illuminating radiation.

Source	Particle	Energy (eV)	Wavelength (pm)	Object
lamp, laser	γ	2	600,000	cell
electron microscope	e	200,000	2.5	molecule
X-ray tube	X	60,000	20	atom
reactor	n	1	30	atom
van de Graaff	p	6,000 000	0.01	nucleus
cyclotron	p	100,000,000	0.003	nucleus
linear accelerator	e	45,000,000,000	0.00003	quark
synchrotron	p	500,000,000,000	0.000002	nucleon*

*Due to its own finite size, a proton cannot probe the interior of another proton despite the very small wavelength.

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

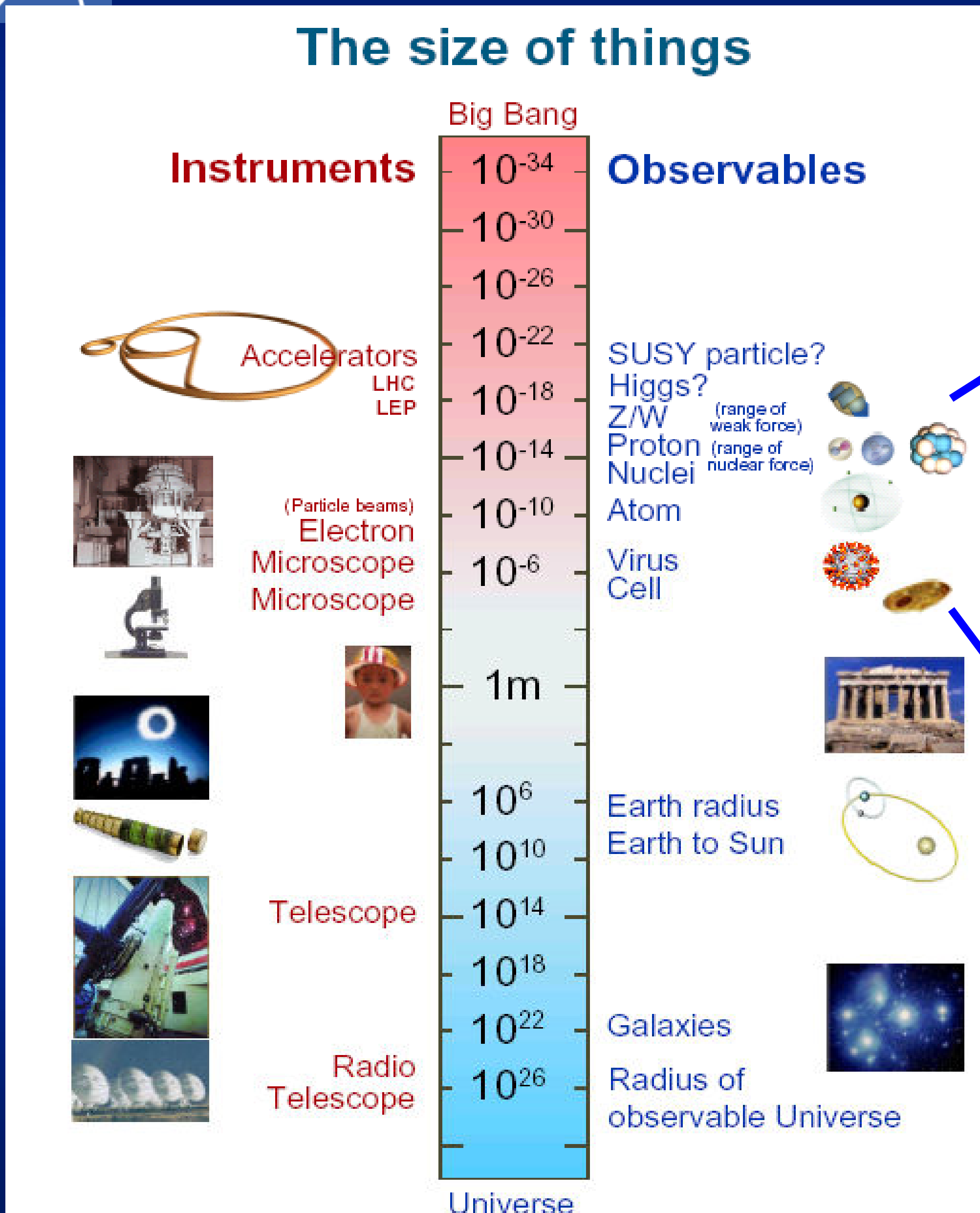
Accelerators: developed in physics labs are used in hospitals

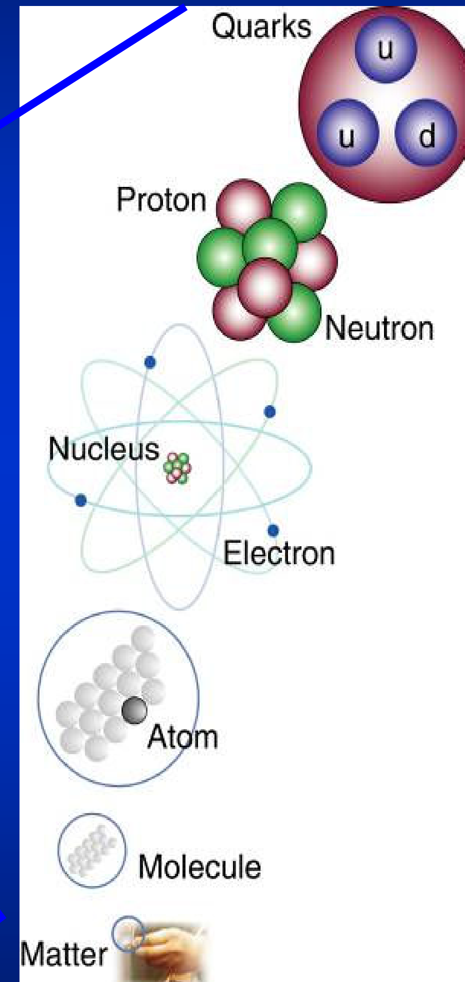


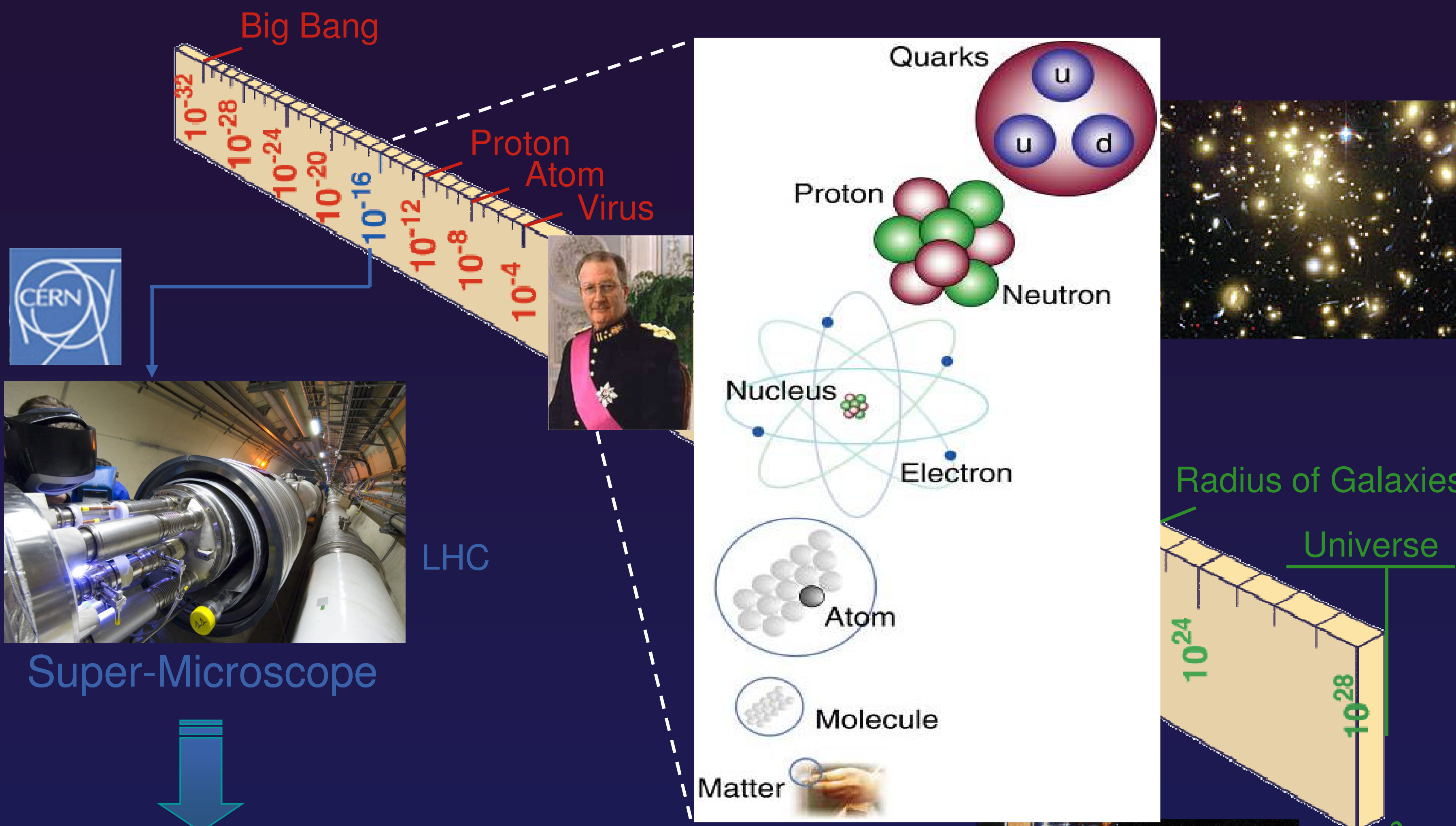
Around 9000 of the 17000 accelerators operating in the World today are used for medicine.

Detectors: developed in physics labs are used for medical imagery

PET (Positron Emission Tomography) is a very important technique for localising and studying certain types of cancer using the Fluor-18 isotope produced by particle accelerators.
PET uses antimatter (positrons).


The size of things
Big Bang
Instruments
Observables
10^{-34}
10^{-30}
10^{-26}
10^{-22}
10^{-18}
10^{-14}
10^{-10}
10^{-6}
1m
10^{6}
10^{10}
10^{14}
10^{18}
10^{22}
10^{26}
Universe
Accelerators
LHC
LEP
(Particle beams)
Electron
Microscope
Microscope
Telescope
Radio
Telescope
SUSY particle?
Higgs?
Z/W
(range of weak force)
Proton
(range of nuclear force)
Nuclei
Atom
Virus
Cell
Earth radius
Earth to Sun
Galaxies
Radius of
observable Universe

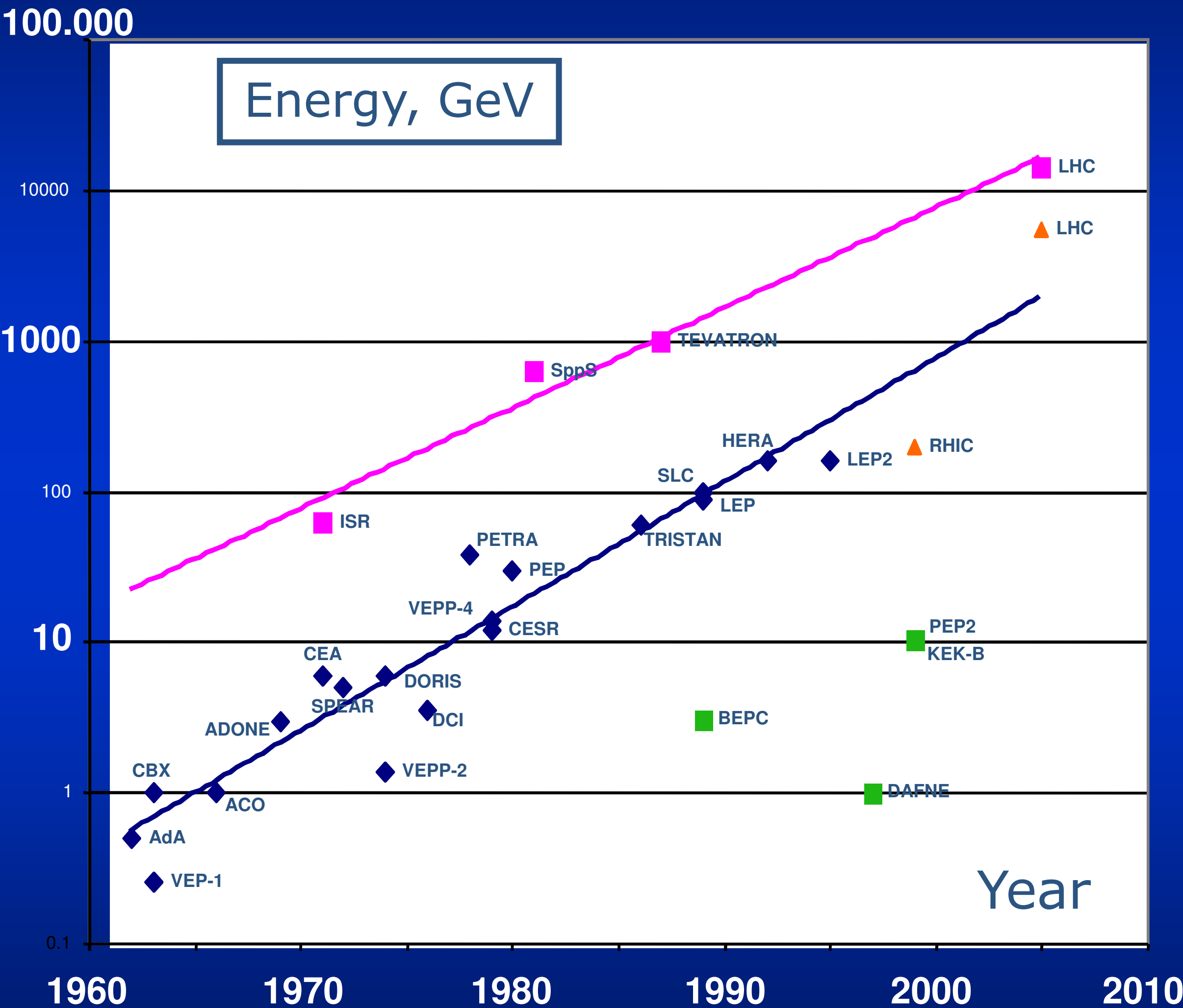

Quarks
u
u
d
Proton
Neutron
Nucleus
Electron
Atom
Molecule
Matter



Study physics laws of first moments after Big Bang

➘ increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

Energy available at Collider facilities vs. time



Equivalent energy in fixed target (P):

Tevatron: P-Pbar, 1987

$E_{equiv} \approx 0.5\ 10^3$ TeV

LEP2: $e^+ e^-$, 1995

≈ same range as Tevatron

LHC: P-P , 2007

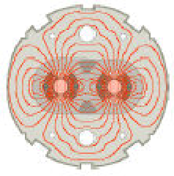
$E_{equiv} \approx 1.1 \bullet 10^5$ TeV

+ X-factories

+Heavy Ions...

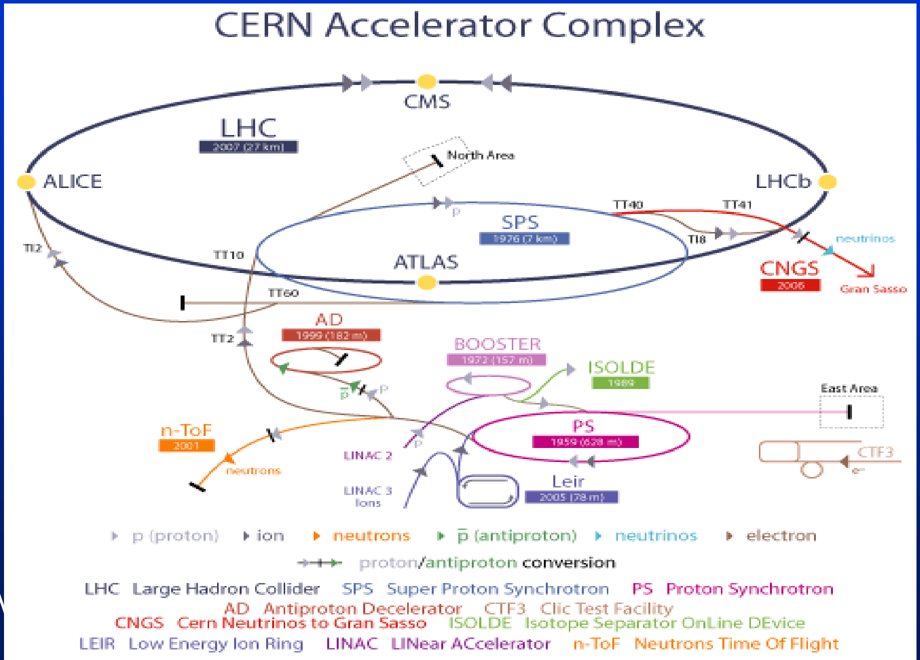
Particle Accelerators

What is a Particle Accelerator ?



- Provides a **beam** of energetic particles to study the structure of matter
- Employs a **vacuum chamber** in which the particles travel
- Employs **electric fields** to impart energy to (accelerate) the particles
- Employs **magnetic fields** to steer and focus the beam
- Makes **collisions** either against a fixed target, or between two beams of particles

Linear accelerator Beam travels from one end to the other	Circular accelerator Beam repeatedly circulates around ring



The main components of an accelerator include

The beam

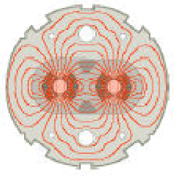
- The name given to a stream of energetic particles moving at speeds very close to that of light. Indeed the choice of name is by analogy to a beam of light.

- Not always continuous – bunches

  - Typical bunch length a few cm
  - Typical transverse size sub mm
  - Typical bunch intensities a few 10^{10} charged particles
  - Typical velocities for accelerator beams are ultra relativistic

LHC injected beam (450GeV)	.999997826c
LHC physics beam (7TeV)	.999999991c
LHC beam	3000 bunches of 10^{11} protons

List of Technologies needed for building and exploiting Accelerators



- Civil engineering
- Survey
- Electrical distribution
- Cooling and Ventilation
- Cryogenics
- Magnets, room temperature and superconducting
- Power converters
- Ultra High Vacuum
- Radio Frequency, room temperature and superconducting
- Beam Instrumentation
- Controls and Databases
- Beam feedback
- Injection, extraction… fast powerful kicker magnets
- Targets, dumps and collimators

Electronics
Large scale simulations
Mechanical engineering
Beam-materials science
……

The main components of an accelerator include

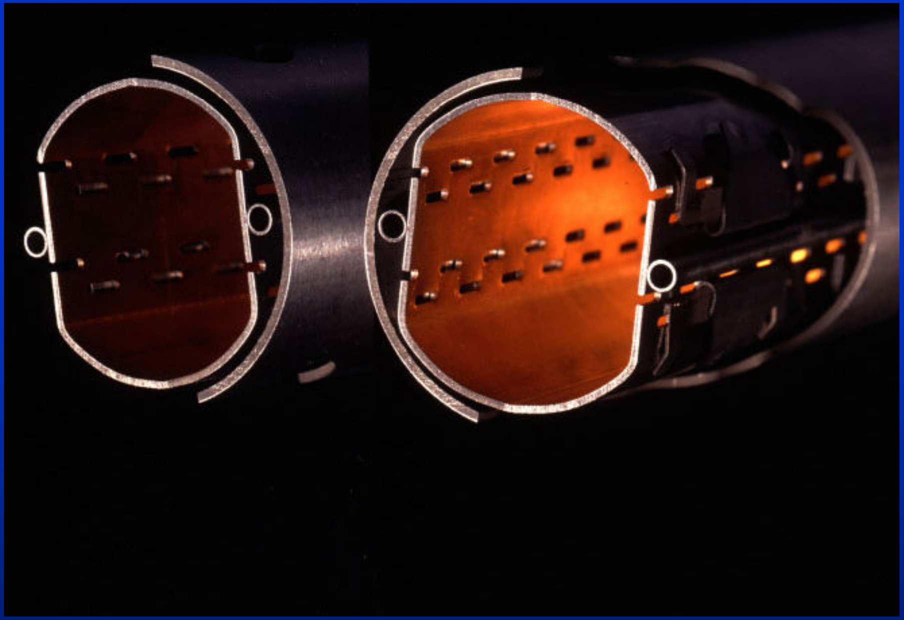
Vacuum chamber

- This is a metal pipe (also known as the beam pipe) inside which the beam of particles travels. It is kept at an **ultrahigh vacuum** to minimise the amount of gas present to avoid collisions between gas molecules and the particles in the beam.

Ultrahigh vacuum 10^{-10} Torr

1 atm = 760 mm Hg = 760 torr
1 atm ~ 1 bar = 100 000 Pa
1 pascal (Pa) = force of 1 Newton per m^2

So 10^{-10} Torr ~ 10^{-10} mbar ~ 10^{-8} Pascal

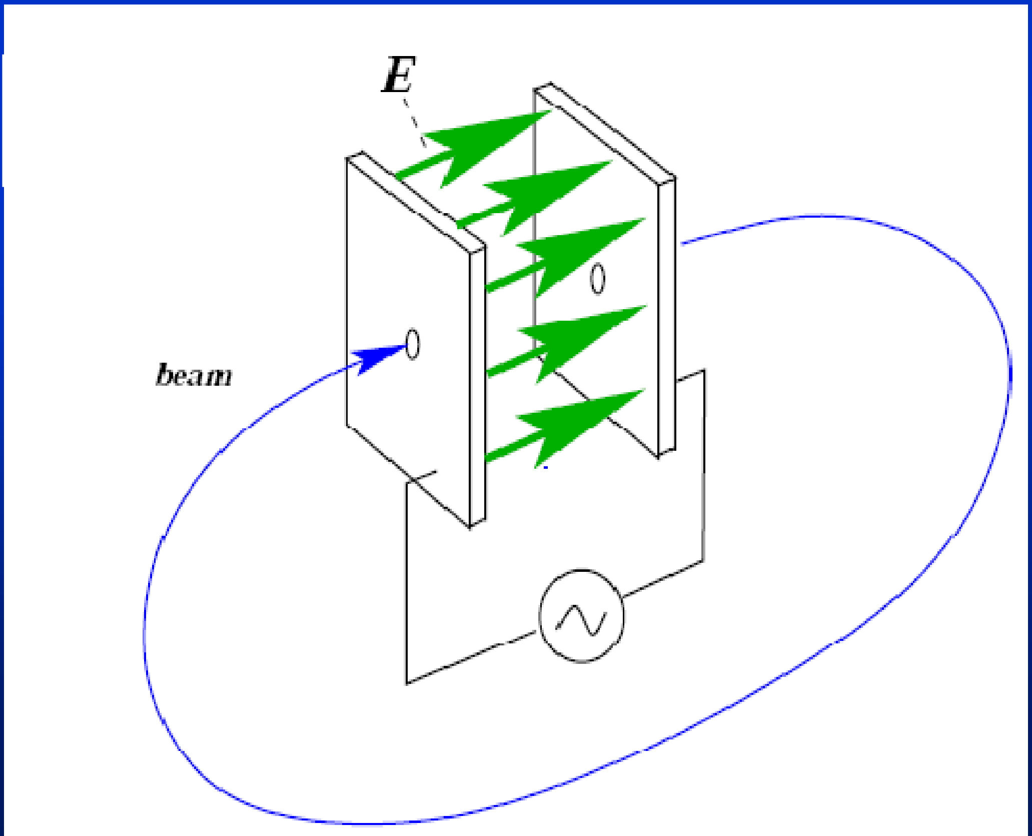


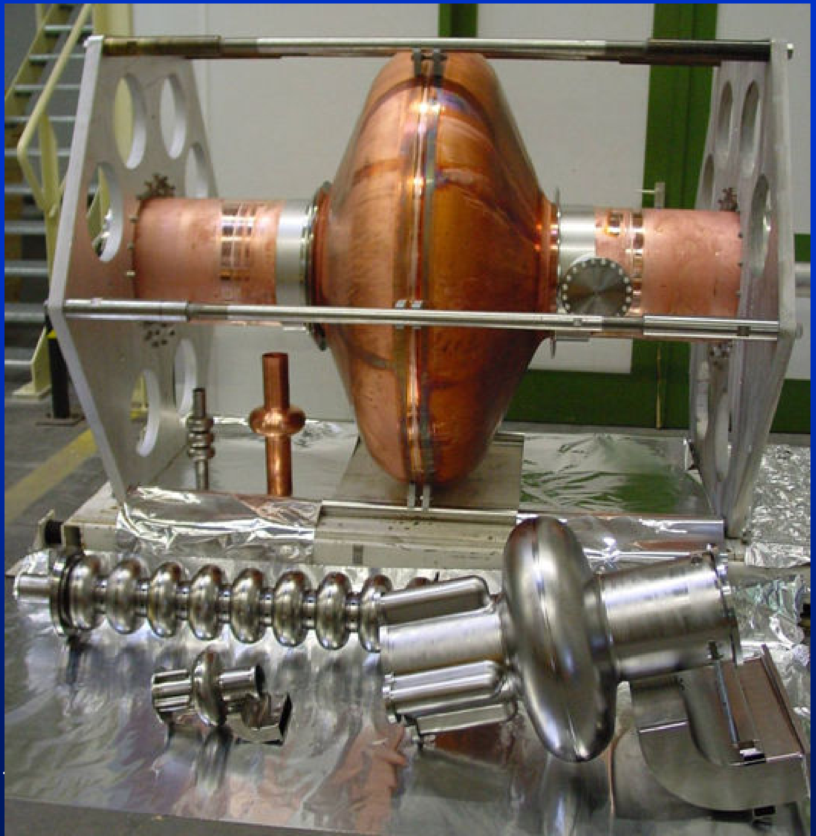
The pressure in the beam-pipes of the LHC will be about ten times lower than on the moon

The main components of an accelerator include

Radiofrequency (RF) electric fields

- **These provide acceleration to a beam of particles. RF cavities are located intermittently along the beam pipe. Each time a beam passes the electric field in an RF cavity, some of the energy from the radio wave is transferred to the particles.**

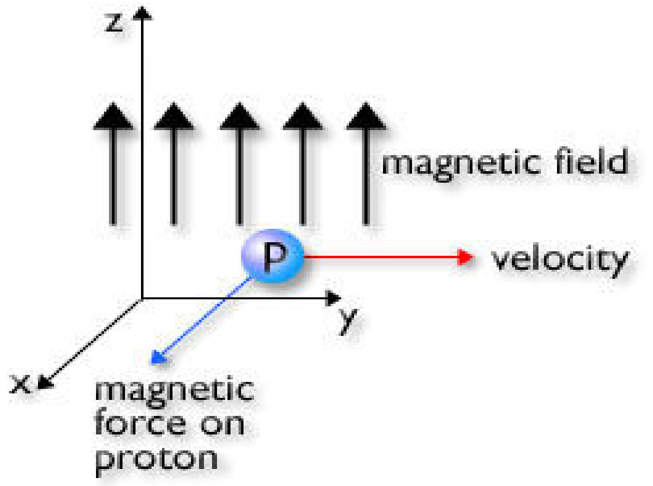


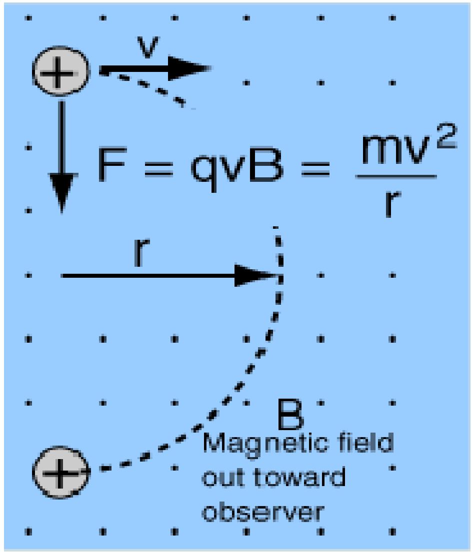


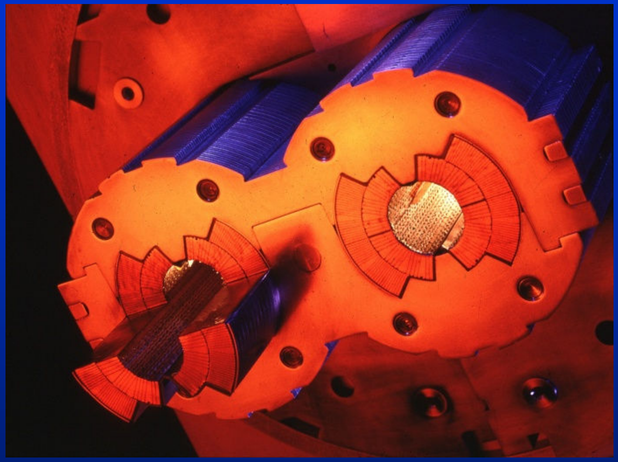
The main components of an accelerator include

Magnetic fields

- **Various types of magnets are used to serve different functions. Dipole magnets are usually used to bend the path of a beam of particles that would otherwise travel in a straight line. The more energy a particle has, the greater the magnetic field needed to bend its path.**



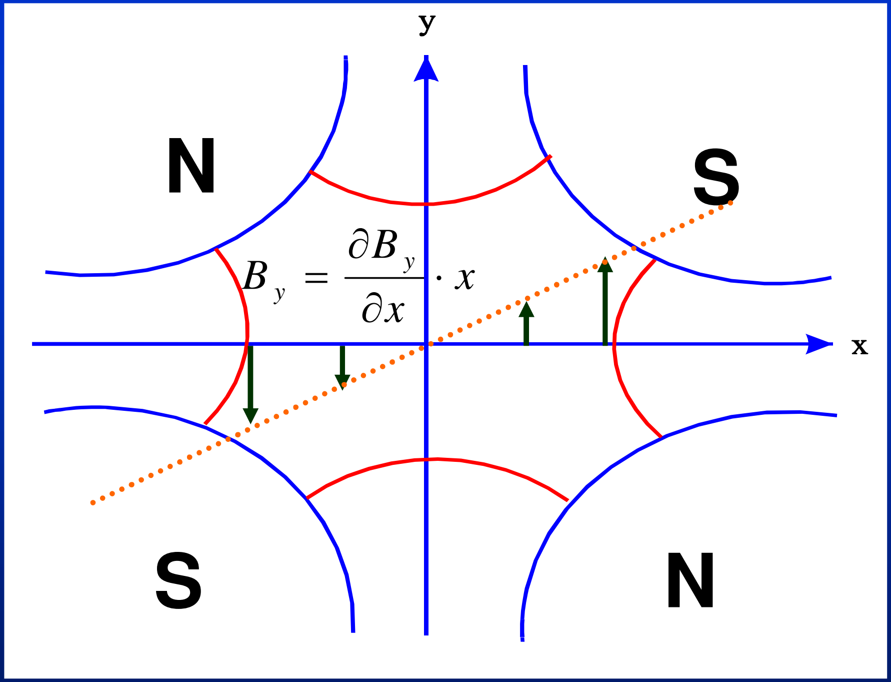


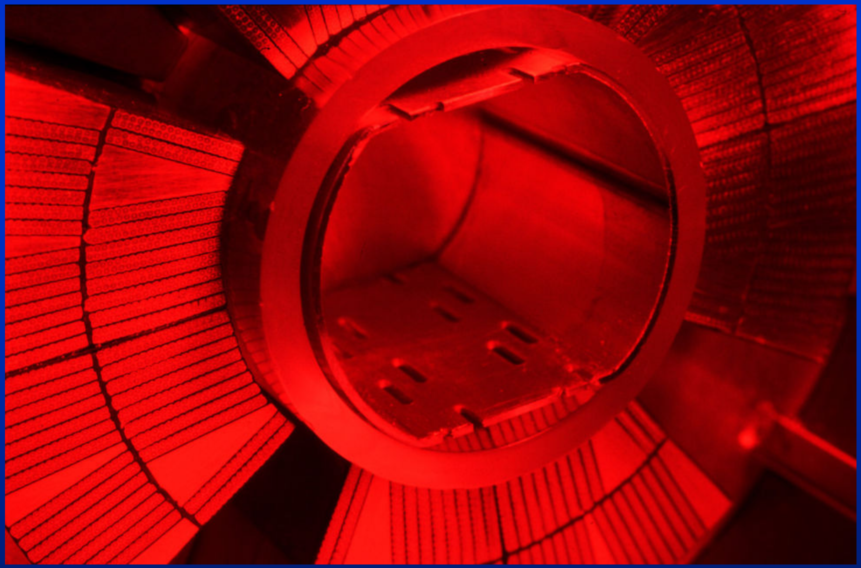


The main components of an accelerator include

Magnetic fields

- Various types of magnets are used to serve different functions. **Quadrupole magnets** are used to focus a beam, gathering all the particles closer together (similar to the way that lenses are used to focus a beam of light).

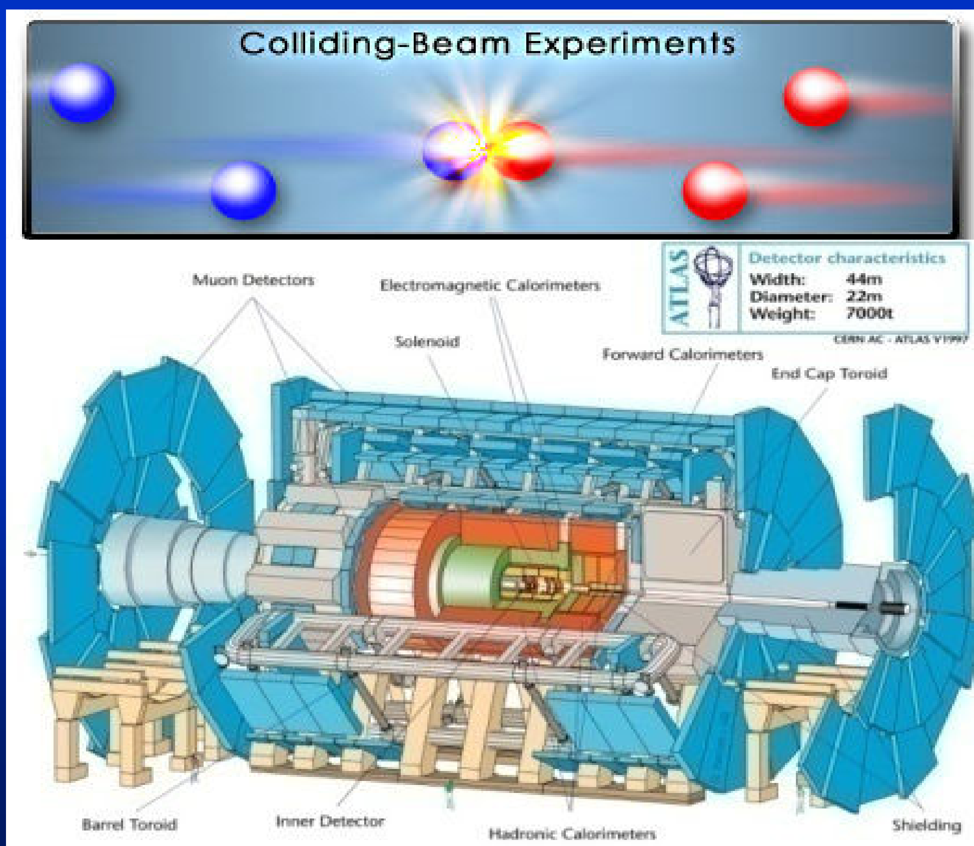


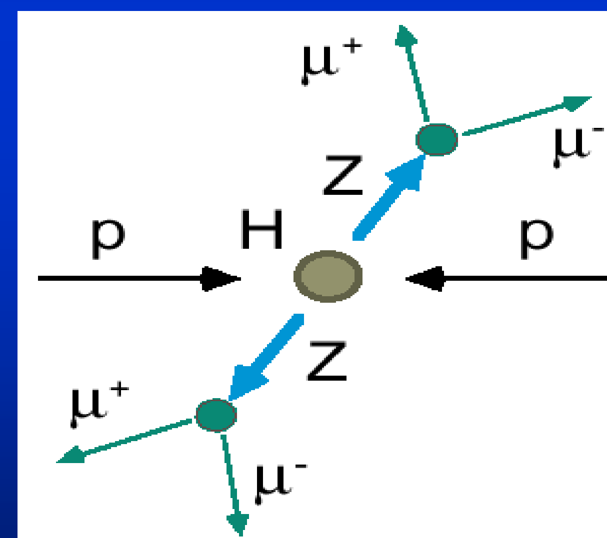


The main components of an accelerator include

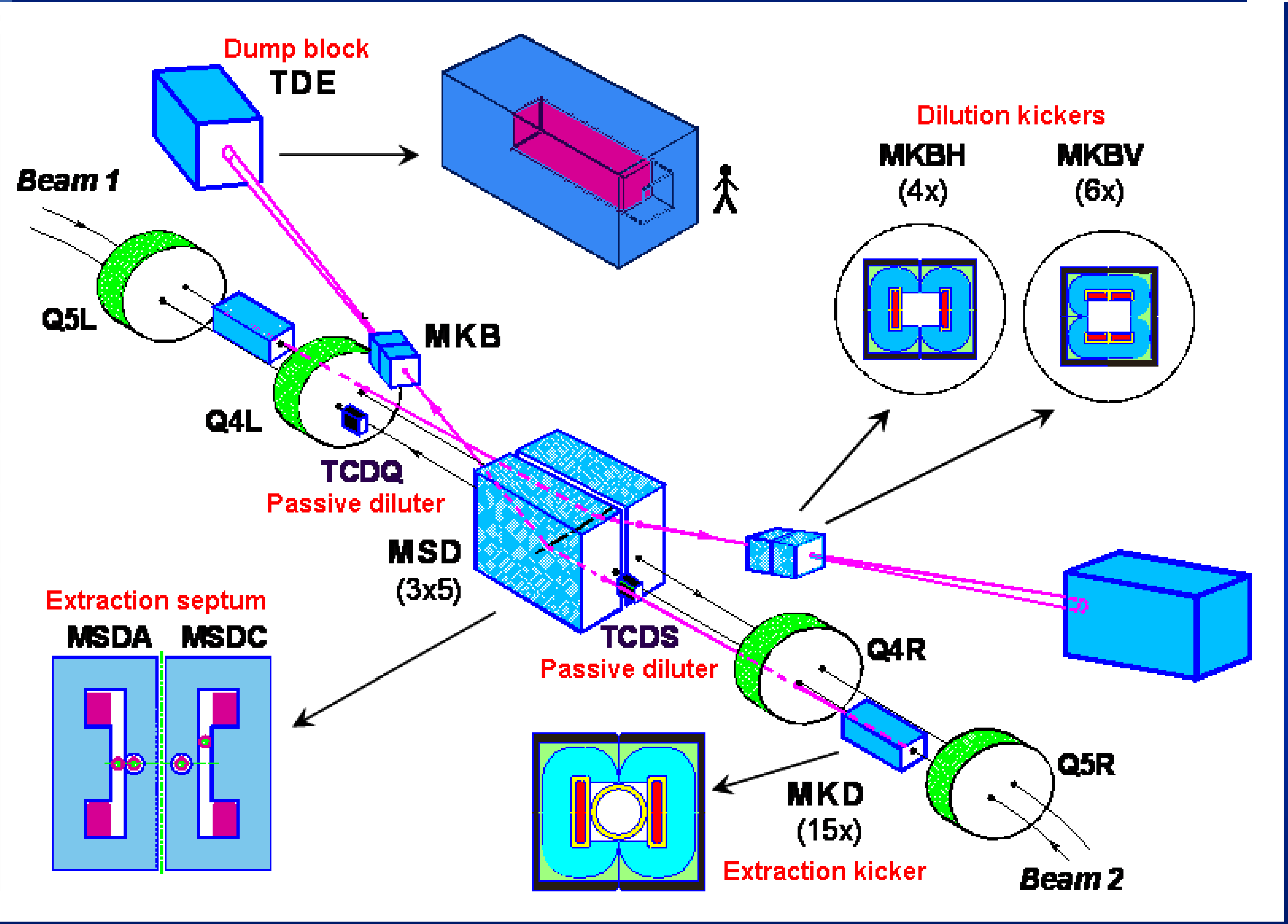
Collisions

- Counter-rotating beams are magnetically steered so that they collide. **Particle detectors** are placed around the collision point to record the particles that emerge from the collision.



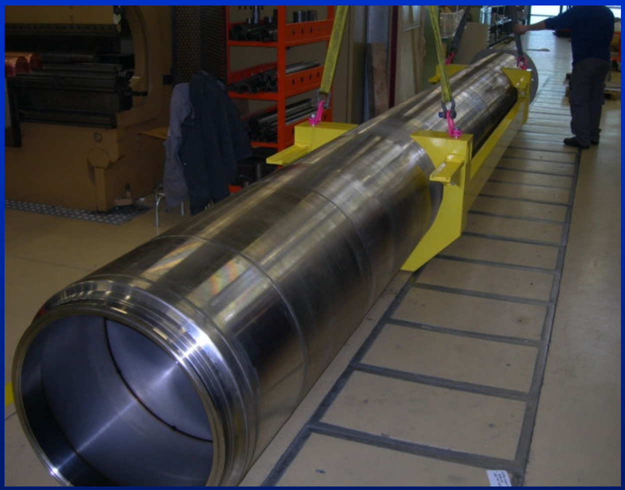


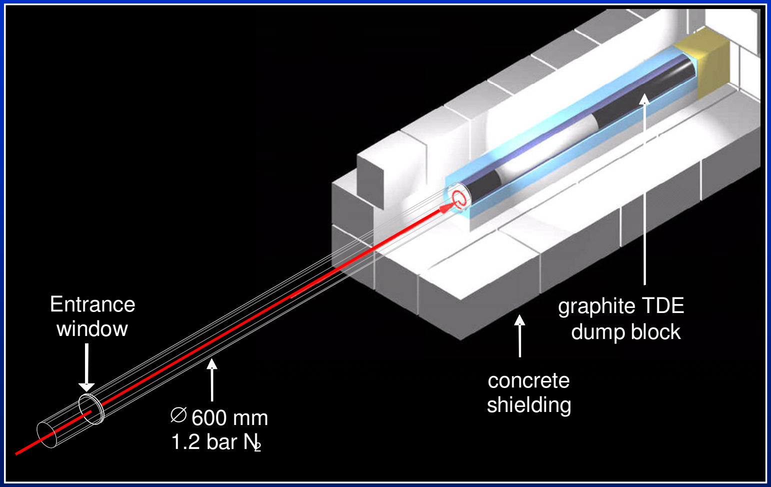
LHC beam dump principle (and acronyms)



Beam dump core (TDE)

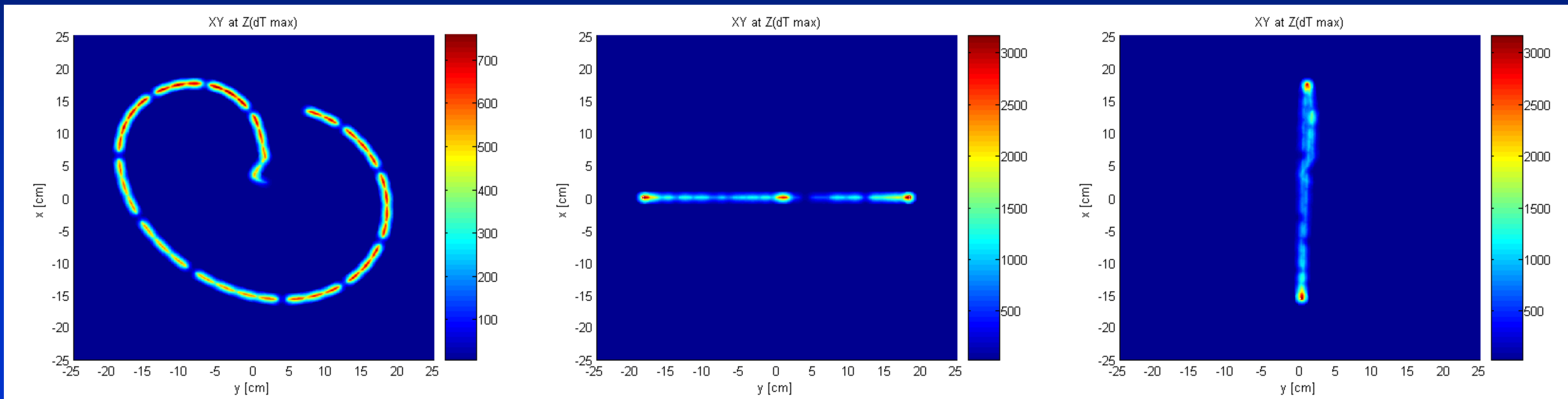
- 7.7m long, 700 mm ∅ graphite core
- Graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, filled with 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks





Beam dump core with dilution failures

Nominal | *0/6 vertical diluters* | *0/4 horizontal diluters*



Nominal beam intensity (3.2×10^{14} p+)

Maximum energy density in dump block

kJ/g		number active MKBV 6	5	4	3	2	1	0
number active MKBH	4	**1.09**	1.17	1.28	1.65	2.44	4.25	7.96
	3	1.33	1.38	1.45	1.67	2.43	4.32	**8.98**
	2	1.74	1.75	1.85	2.01	2.50	4.50	**11.30**
	1	2.74	2.89	2.87	2.99	3.36	4.74	**16.03**
	0	6.67	7.56	**8.41**	**9.90**	**12.70**	**17.44**	**53.29**

Maximum temperature rise in dump block

K		number active MKBV 6	5	4	3	2	1	0
number active MKBH	4	**761**	804	867	1060	1455	2308	**3727**
	3	894	919	954	1069	1451	2340	**3727**
	2	1105	1110	1164	1244	1482	2425	**3727**
	1	1603	1670	1661	1720	1895	2534	**3727**
	0	3397	**3727**	**3727**	**3727**	**3727**	**3727**	**Vapour**

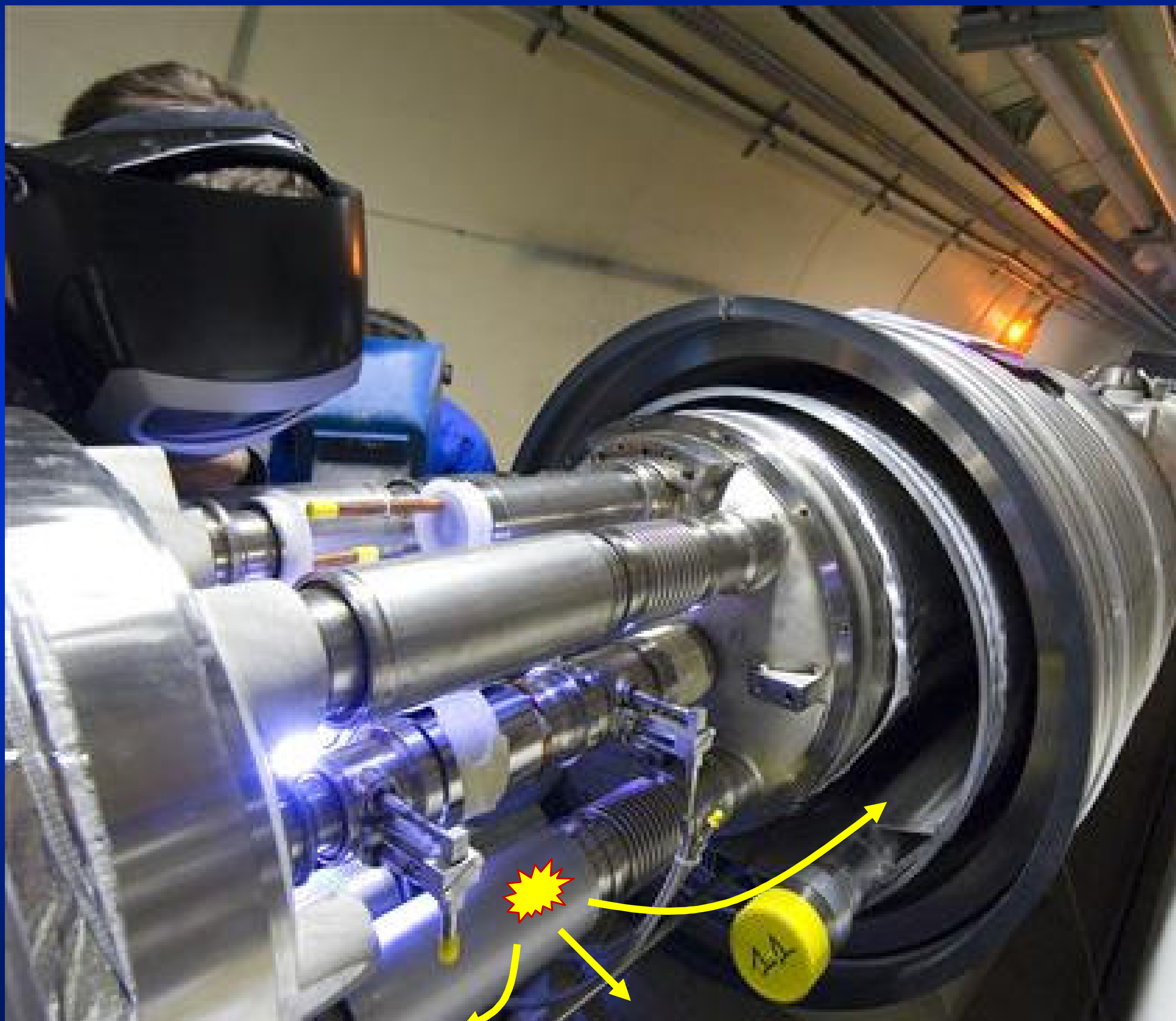
31 kJ/g for onset of sublimation, 60 kJ/g for complete vaporization

LHC Beam Dumping System

MKD:
2 x 15 Systems

Magnet operates in air with coated ceramic chambers

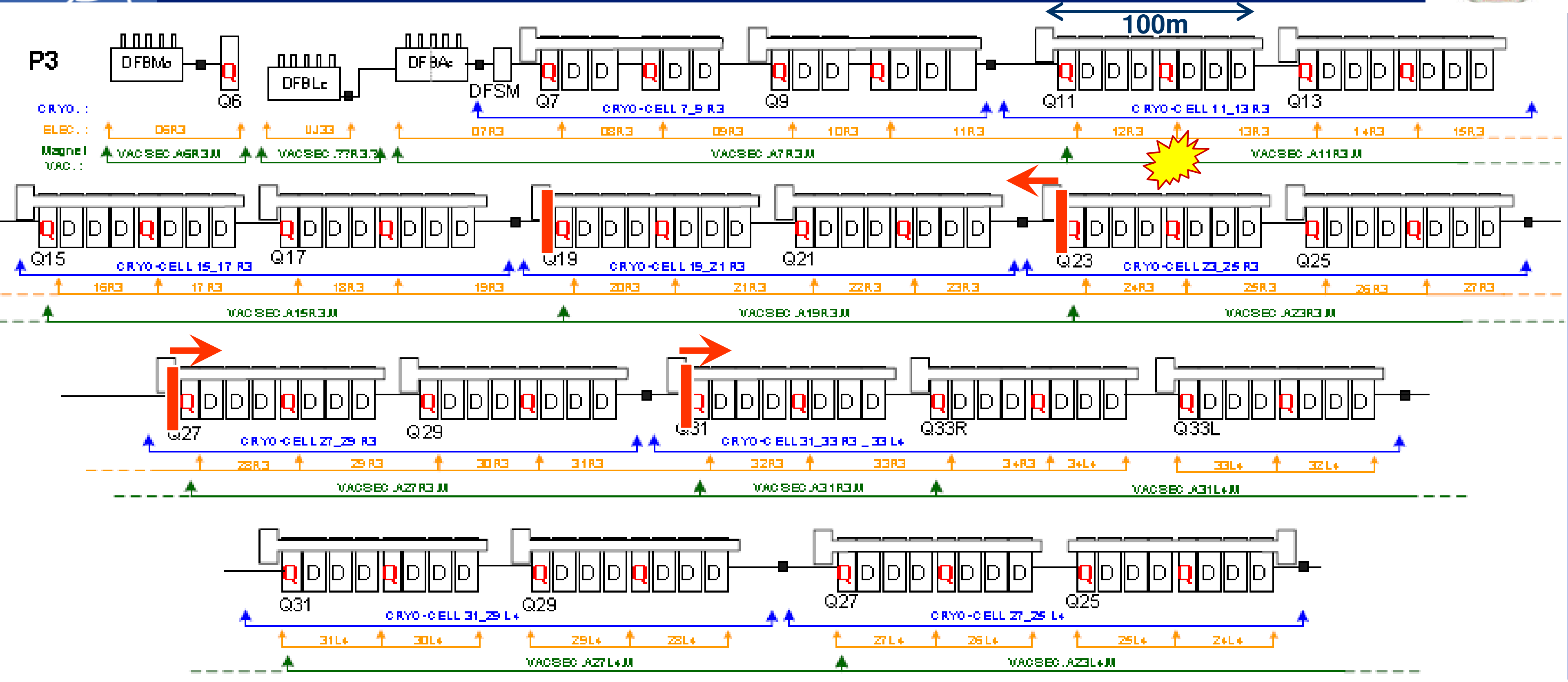
Helium released into the insulating vacuum



Liquid
to
Gas
Expansion
Factor

1000

Consequences



Insulating vacuum barrier every 2 cells in the arc → Some moved

- Considerable collateral damage over few hundred metres
- Damage to superinsulation blankets
- Contamination (by soot and insulation blankets) of beam pipes
- Large release of helium into the tunnel (6 of 15 tonnes)

Construction and commissioning 2002-2008

Tunnel activity determined by

LEP	Helium Distribution Line	Triplet	Cryo

2002	2003	2004	2005	2006	2007	2008

Magnet tests

PC SC tests

Magnet installation

Magnet interconnects

Required magnet storage ☹

Allowed magnet sorting ☺

Definitive cooldown and commissioning for 5TeV

Breakdown

Sector 78 commissioning

Sector 45 commissioning

Beam

Construction and commissioning 2002-2008

Tunnel activity determined by

Helium Distribution Line

2002	2003	2004	2005	2006	2007	2008

Magnet tests

Cryostating the cold masses

Cold testing all magnets

Construction and commissioning 2002-2008

Tunnel activity determined by

Helium Distribution Line

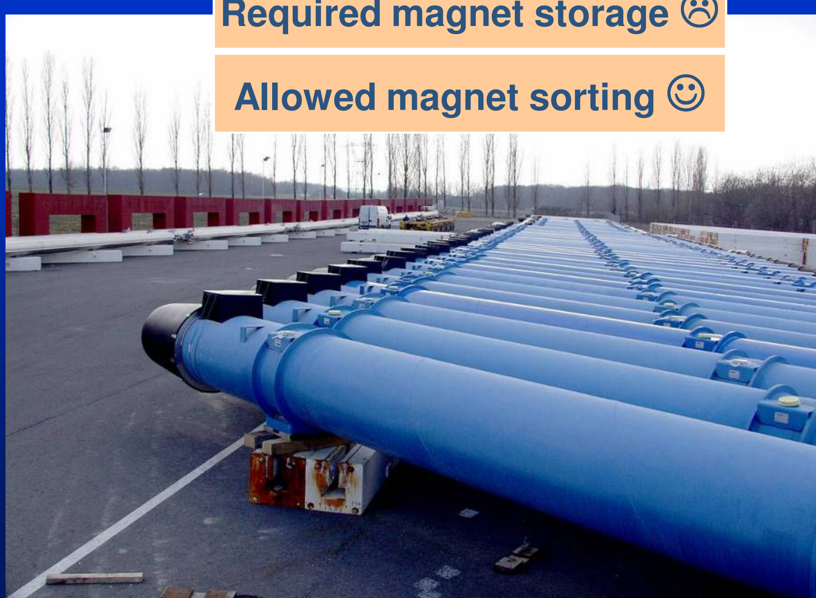
2002	2003	2004	2005	2006	2007	2008

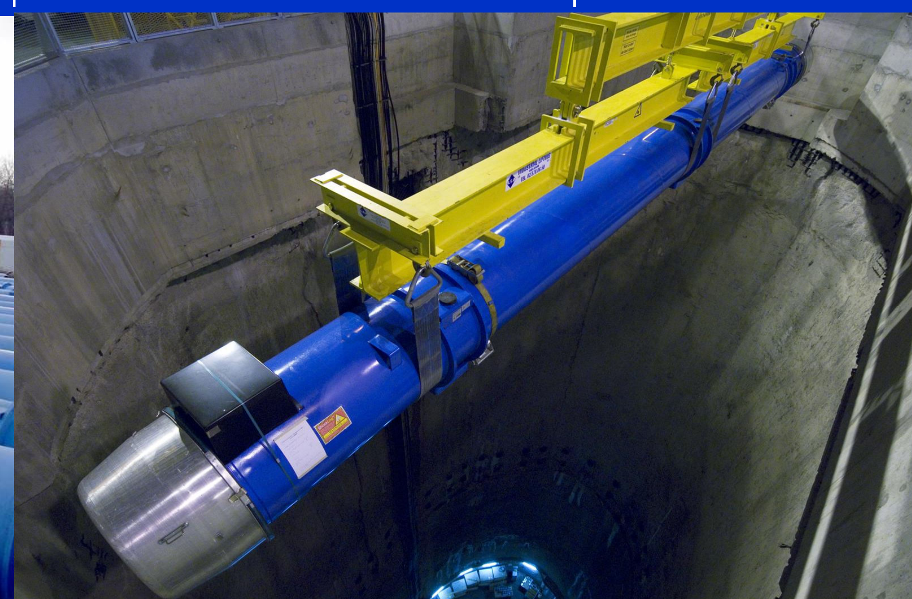
Magnet tests

Magnet installation

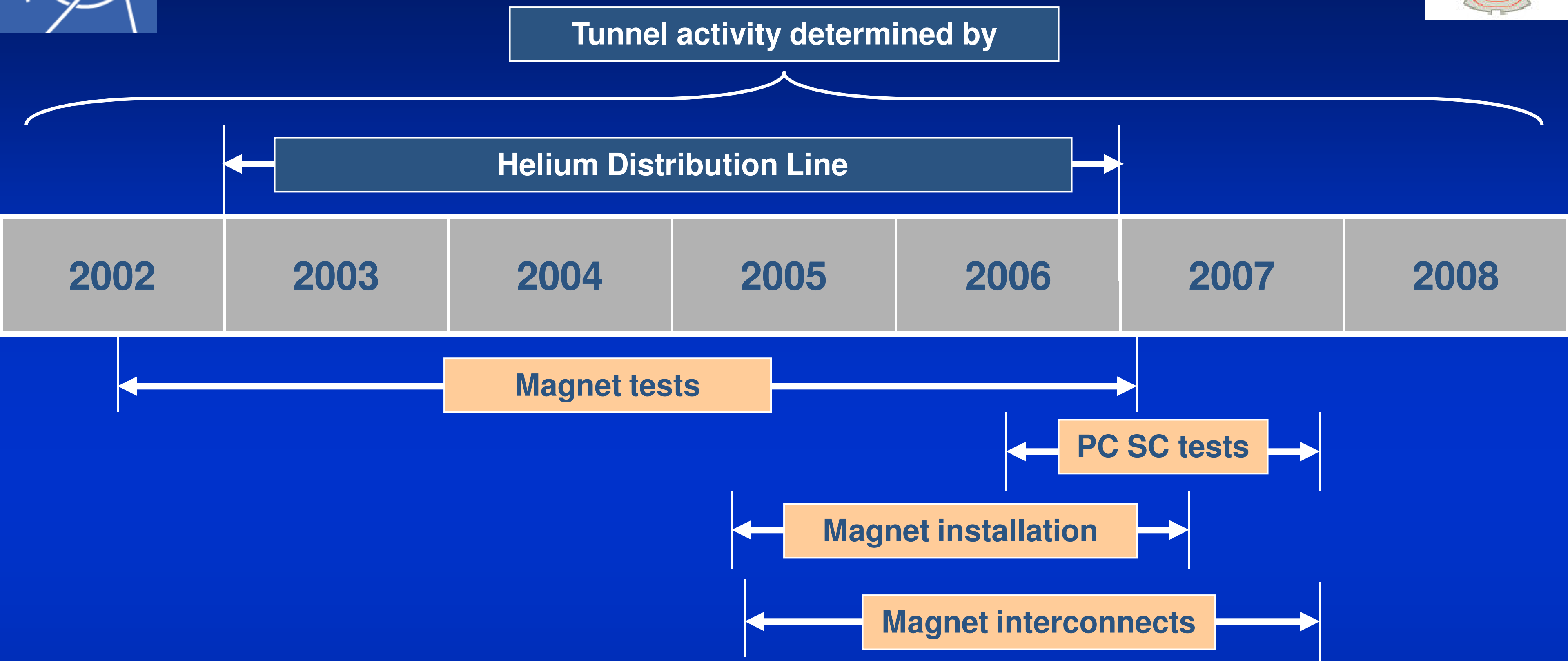
Required magnet storage ☹

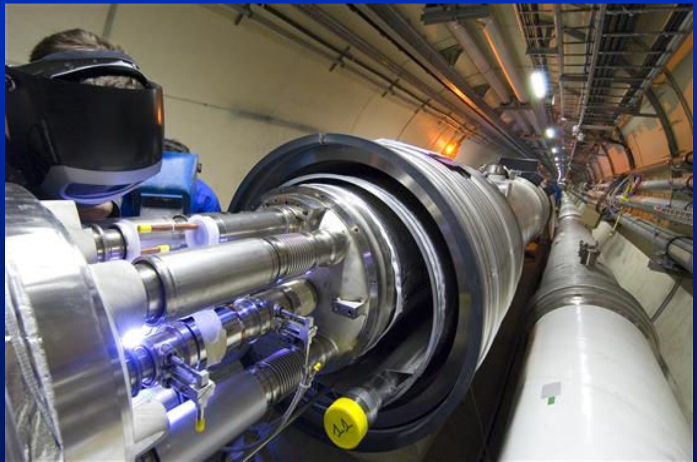
Allowed magnet sorting ☺





Construction and commissioning 2002-2008





September 10th

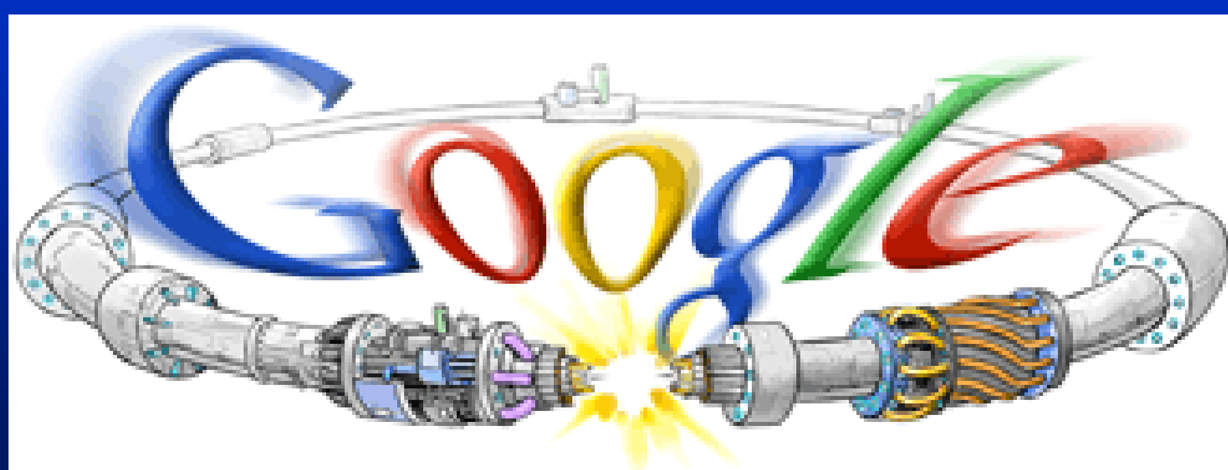
- Single bunch of protons $3\ 10^9$

- Achieved
  - Beam 1 injected IP2
  - Threaded around the machine in 1h
  - Trajectory steering gave 2 or 3 turns

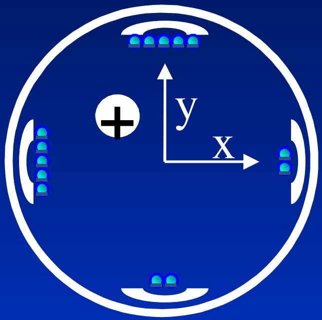
  - Beam 2 injected IP8
  - Threaded around the machine in 1h30
  - Trajectory steering gave 2 or 3 turns
  - Q and Q' trims gave a few hundred turns

No Major Obstacle

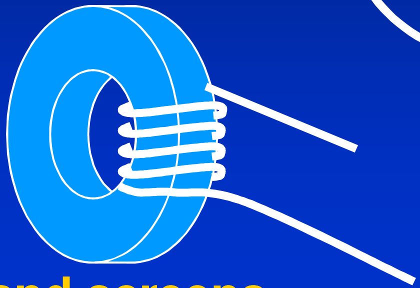
No Major Magnetic Problem

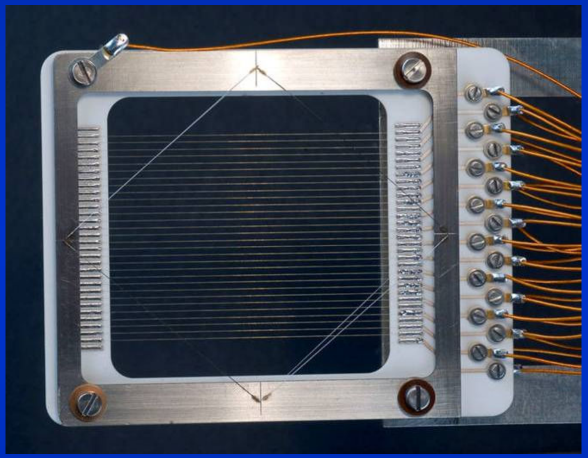


Beam instrumentation (our eyes and ears)



- Beam Position
  - electrostatic or electromagnetic pick-ups
- Beam Intensity
  - beam current transformers





- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
- Beam Loss
  - ionisation chambers or pin diodes

Black Holes
Is LHC Safe?

Is the LHC safe ?

Colliders

Event rate = Luminosity x Cross section

Event rate at 14 TeV $= 10^{34}\ cm^{-2}\ s^{-1} \times 100 * 10^{-27}\ cm^{2}$

$= 10^{9}$ events per second

$= 10^{16}$ events per year of LHC

$= 10^{17}$ events per LHC

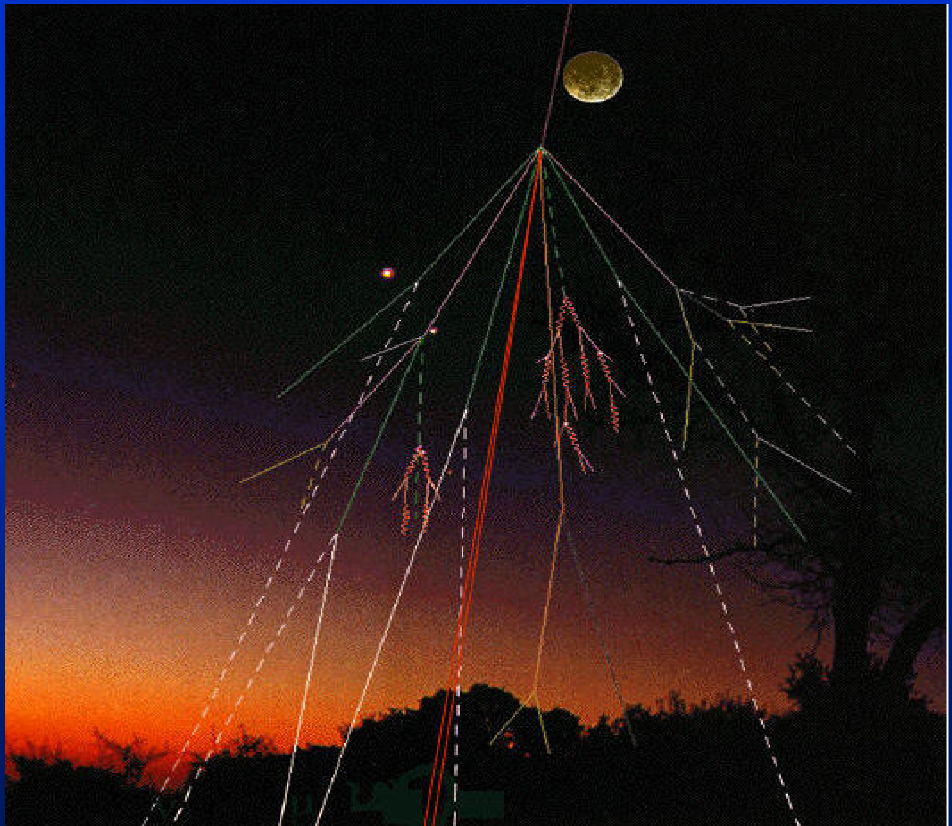
Is the LHC safe ?

Cosmic rays

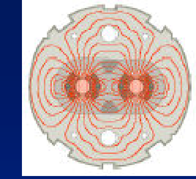
LHC at 14 TeV = Cosmic rays at 100,000 TeV

Event rate = Cosmic ray flux measurements x age of the universe

Event rate above 10^5 TeV = 3 10^{22} events so far



Is the LHC safe ?



So just on Earth

Nature has already performed 10^5 LHC "10 year" programs

And the Earth is still here

And the Sun is 10^4 times the area of the Earth

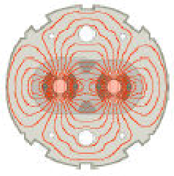
And the Sun is still here i.e. 10^9 LHC "10 year" programs

And there are 10^{11} stars in our galaxy

And there are 10^{11} galaxies in the Universe

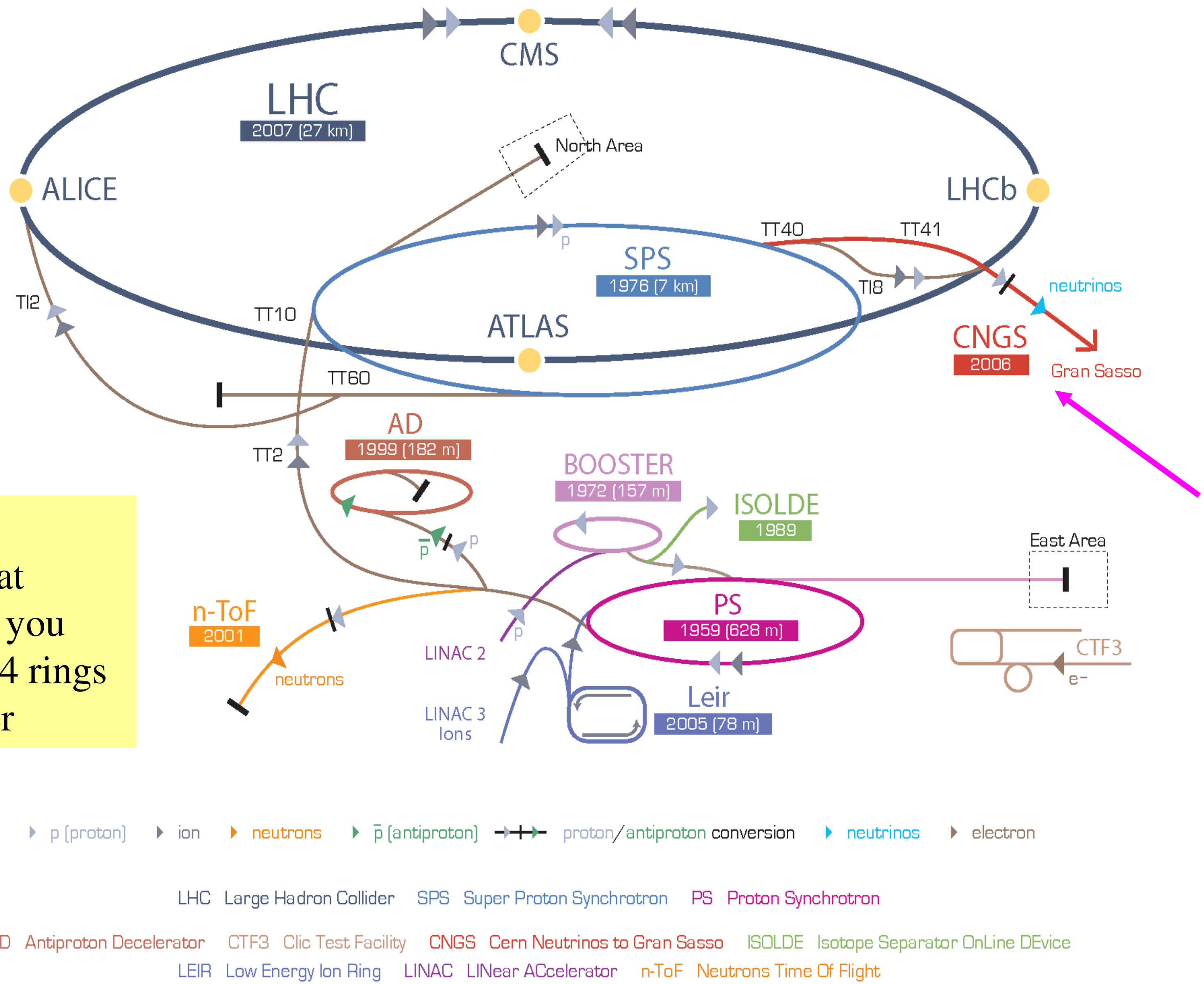
The answer is YES

S.B. Giddings and M. Mangano, *http://arXiv.org/pdf/0806.3381*
LSAG, *http://arXiv.org/pdf/0806.3414*
Scientific Policy Committee Review, *http://indico.cern.ch/getFile.py/access?contribId=20&resId=0&materialId=0&confId=35065*
CERN public web page, *http://public.web.cern.ch/public/en/LHC/Safety-en.html*



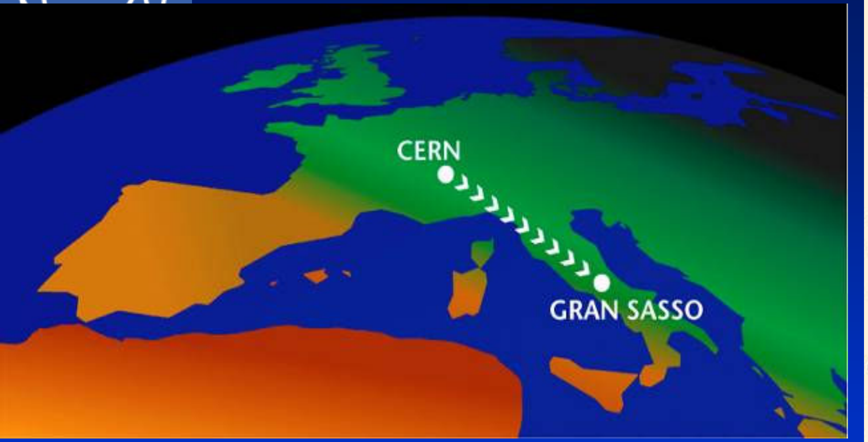
Cern’s Other Accelerators

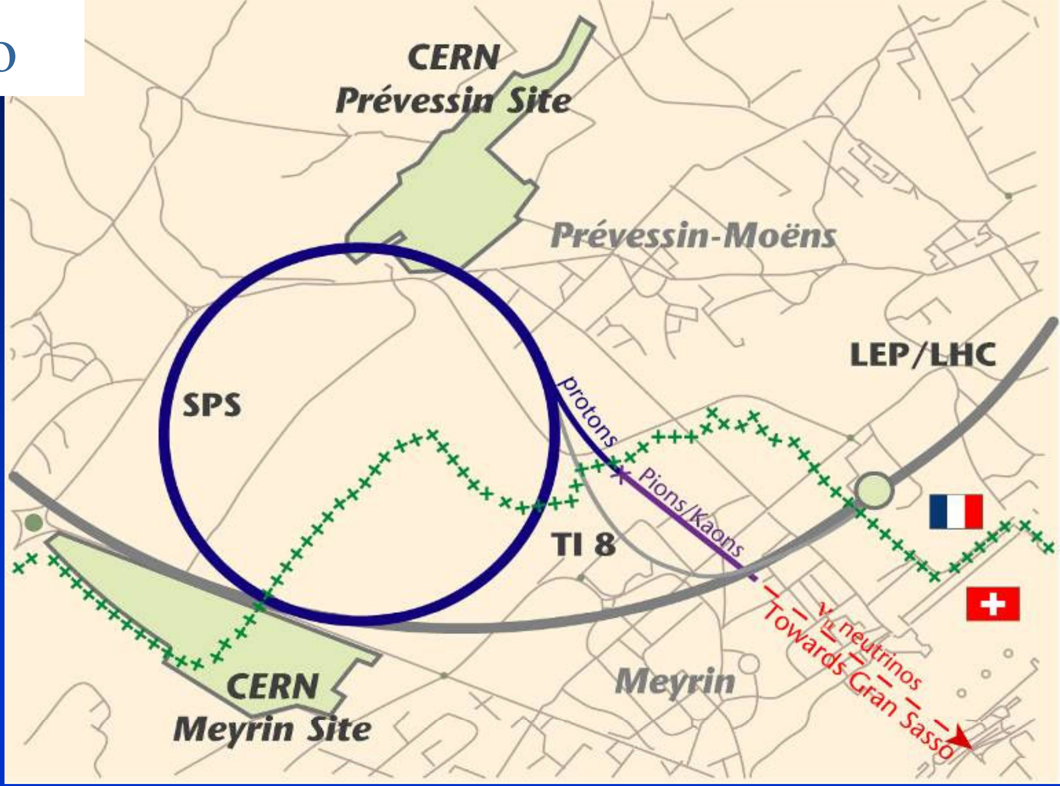
CERN Accelerator Complex



Total of 9 accelerators at CERN, 12 if you consider the 4 rings of the booster

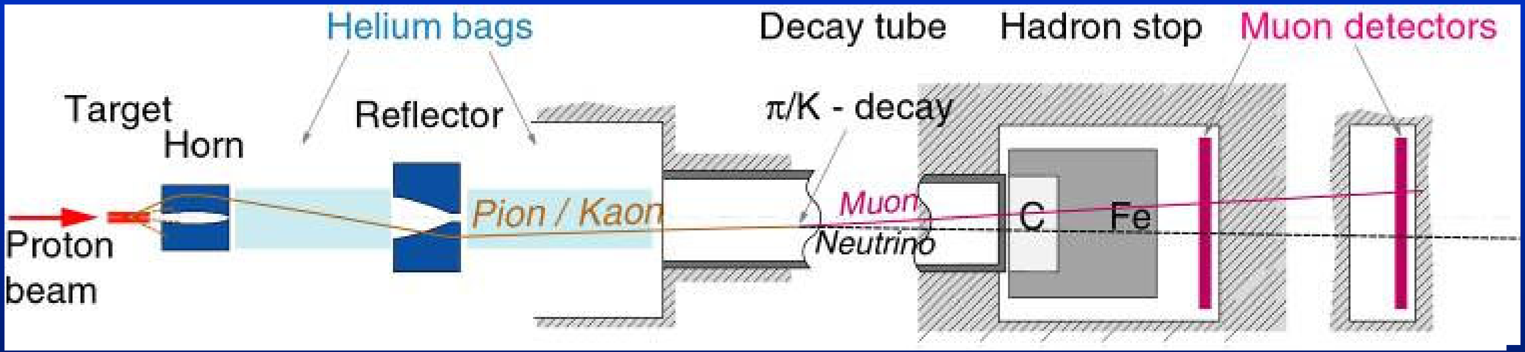
CERN Neutrinos to Gran Sasso



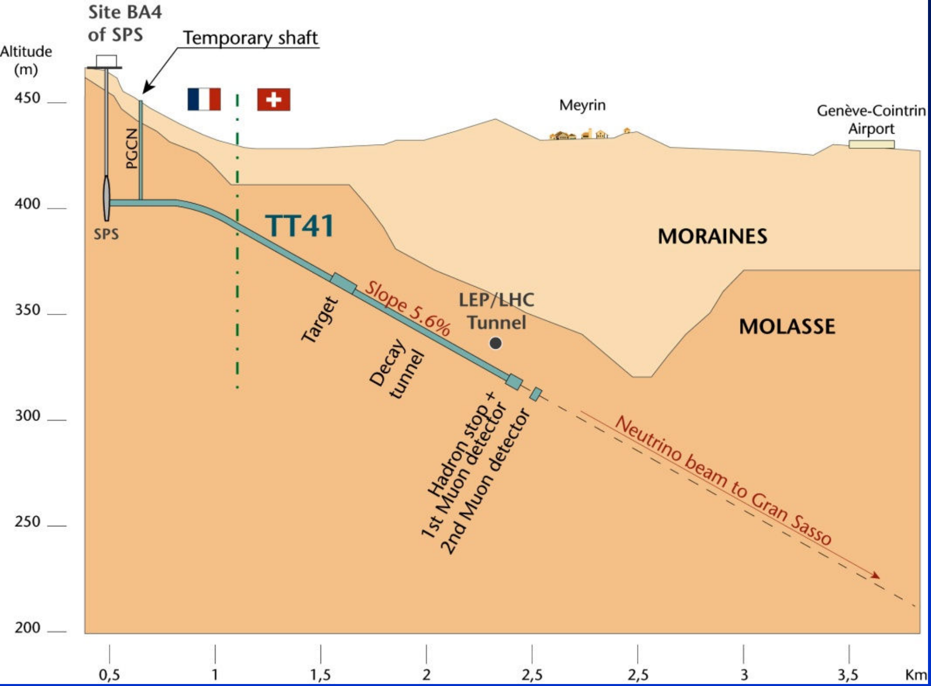


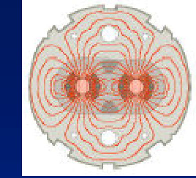
Task for CERN:
produce intense ν_μ beam towards Gran Sasso

700 m 100 m 1000m 67 m

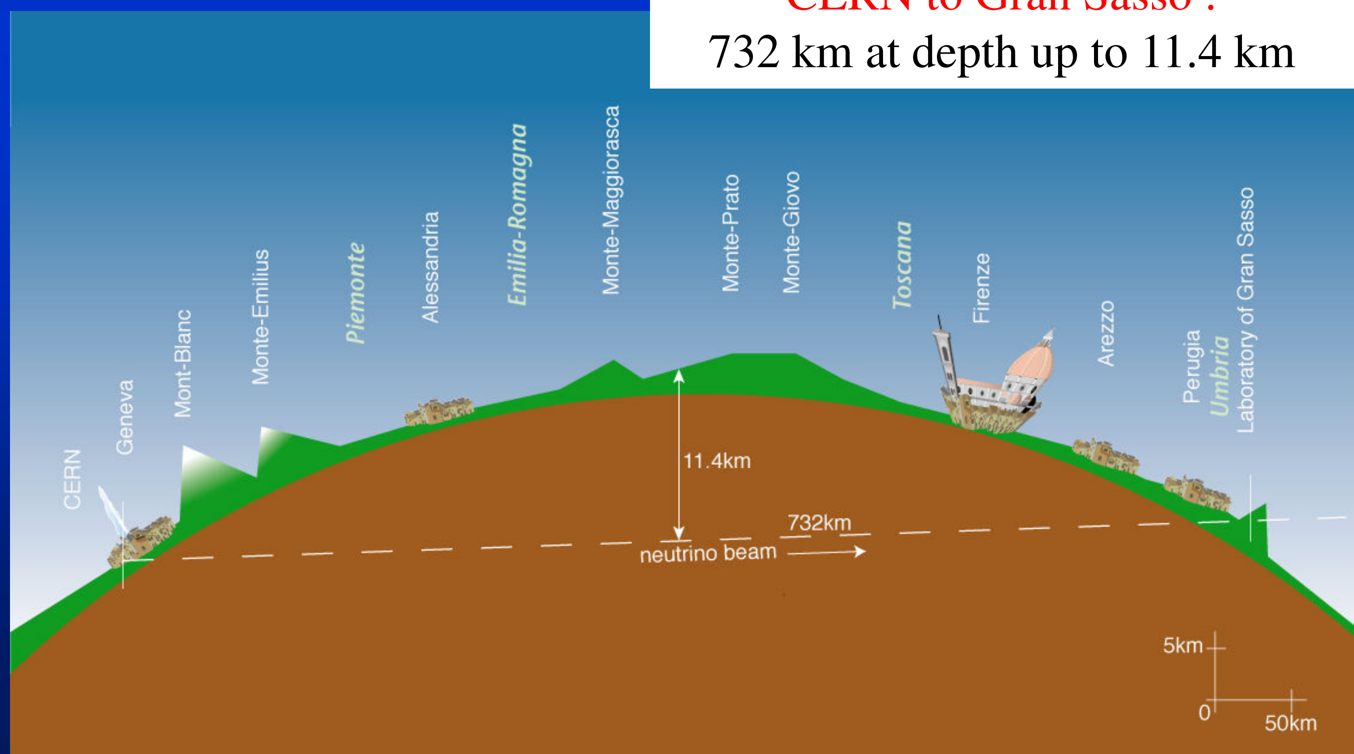


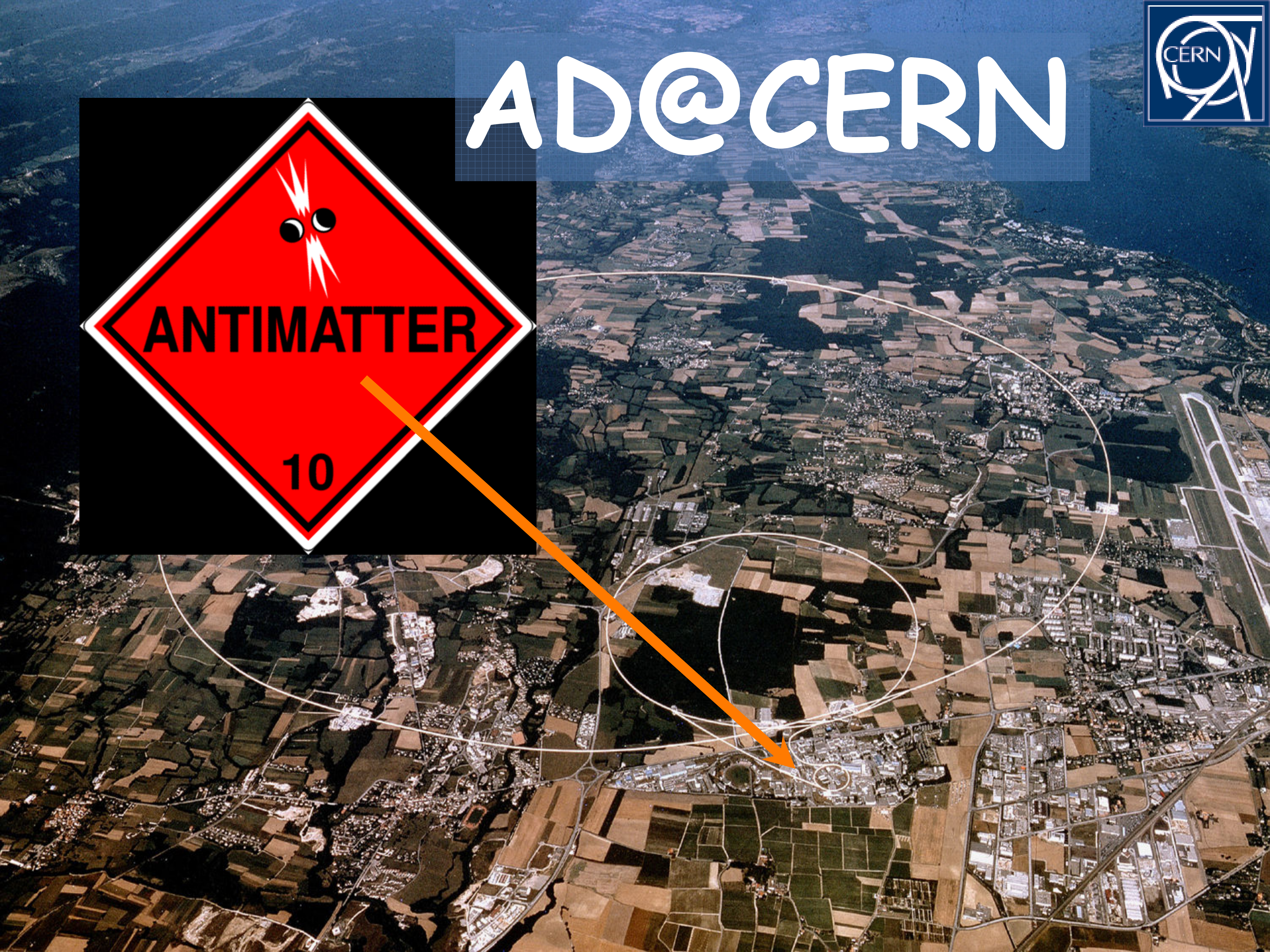
$$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+,\ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$



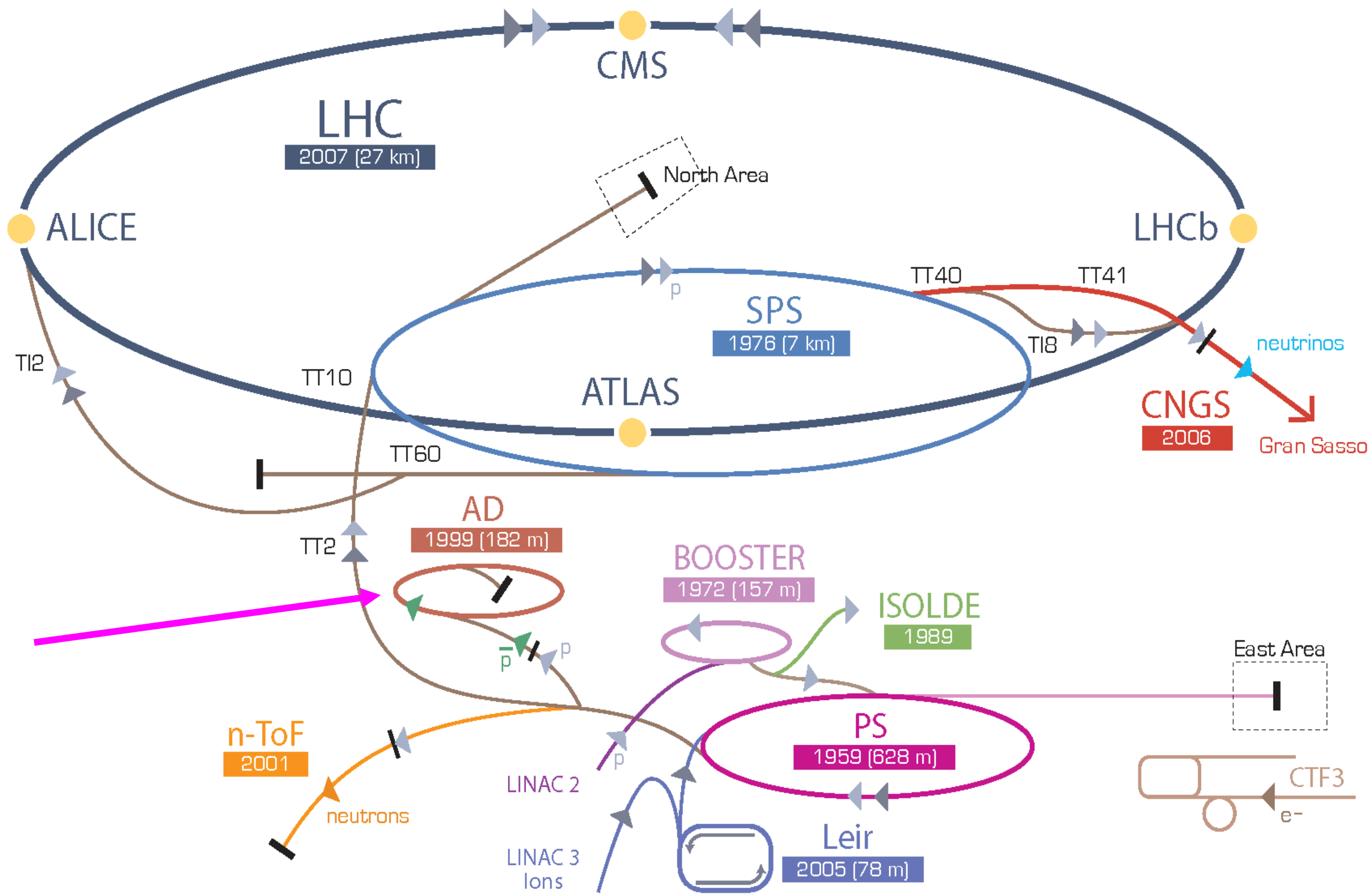


CERN to Gran Sasso :
732 km at depth up to 11.4 km




AD@CERN
ANTIMATTER
10
CERN

CERN Accelerator Complex



p (proton) ion neutrons $\bar{p}$ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

What is antimatter?

$E=mc^2$

Einstein: mass is condensed energy

$(i\gamma^\mu\partial_\mu - m)\psi = 0$

Dirac: particles come in pairs (particle & antiparticle)

Electron Positron

Matter and antimatter are symmetric

Antimatter in the Universe

BigBang: 50:50

Now: 0:100 (1)

verse expands from the size of needle tip

atter are formed in equal quantities

s

all antimatter annihilates

forms stars, galaxies

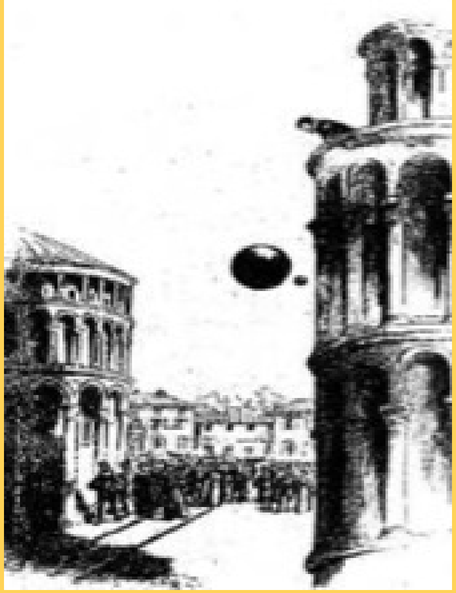
requires matter-antimatter asymmetry

pace (AMS) and in balloons (PAMELA)

Antimatter at CERN

1) Experiments to compare the light emitted by Hydrogen and Antihydrogen atoms (ATRAP, ALPHA)

2) Experiments to measure the fall of antimatter (AEGIS)




Angels & Demons

Dan Brown's

Dan Brown's

Plot summary:
Anti-matter bomb made at CERN is used to attempt to blow up the Vatican

Part truth, part fiction…but mostly fiction!!!!

CERN
European Centre
for Particle Physics
Geneva, Switzerland

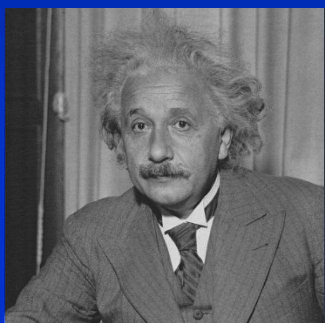
2009

Will we destroy Rome ?

Tom’s Angels and demons

Technological Spin off

Fundamental research has always been a driving force for innovation

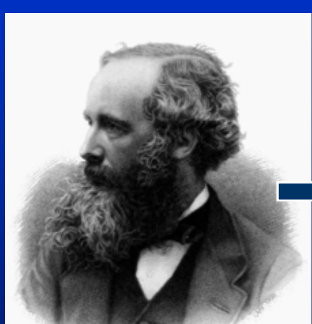


A. Einstein

Relativity

100% SCIENCE

For GPS to work, we have to take into account the correction due to time dilation. Otherwise, there would be a position error of around 10m after just 5 minutes of travel-time!



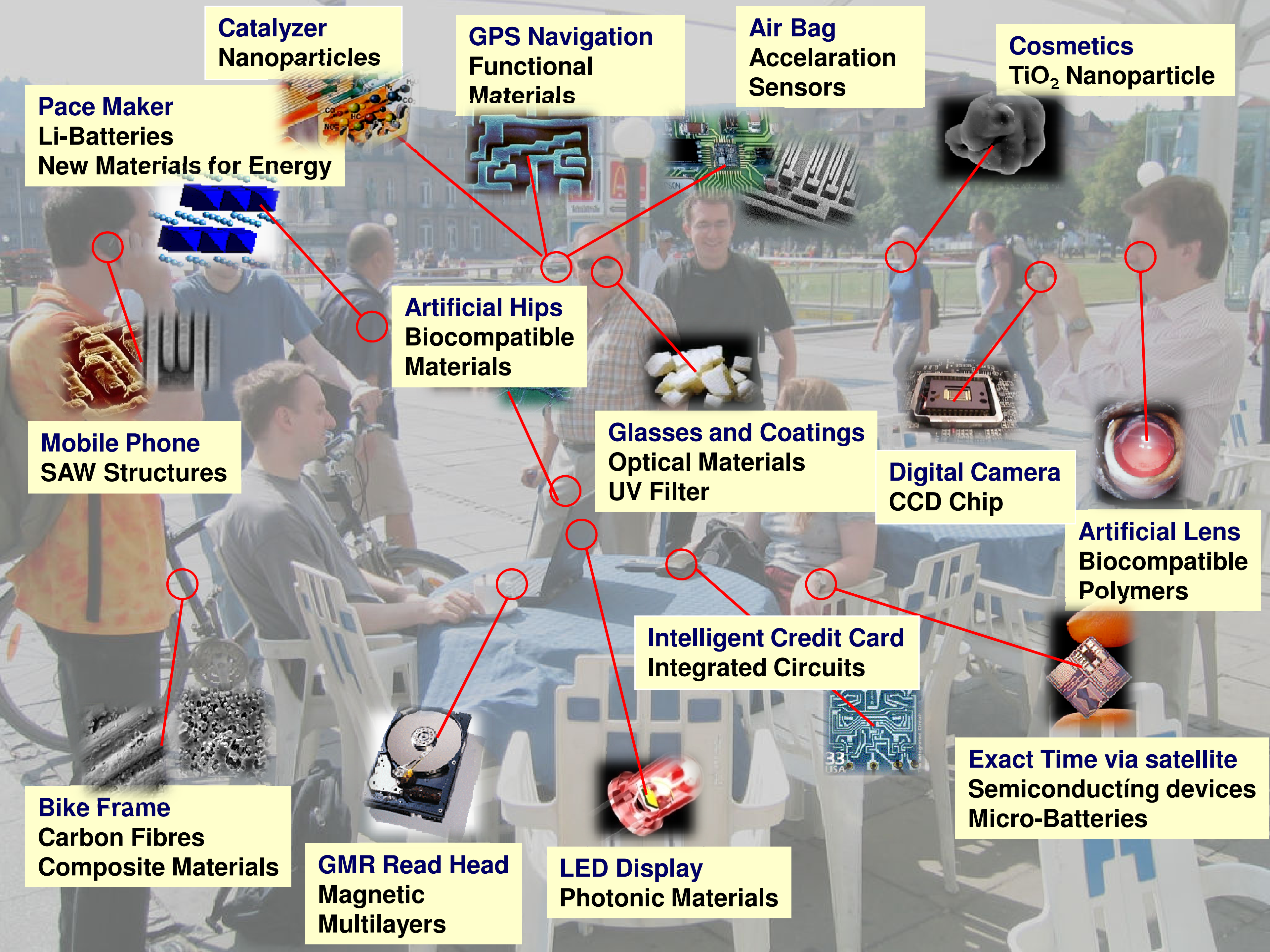
J.C. Maxwell

Electromagnetism

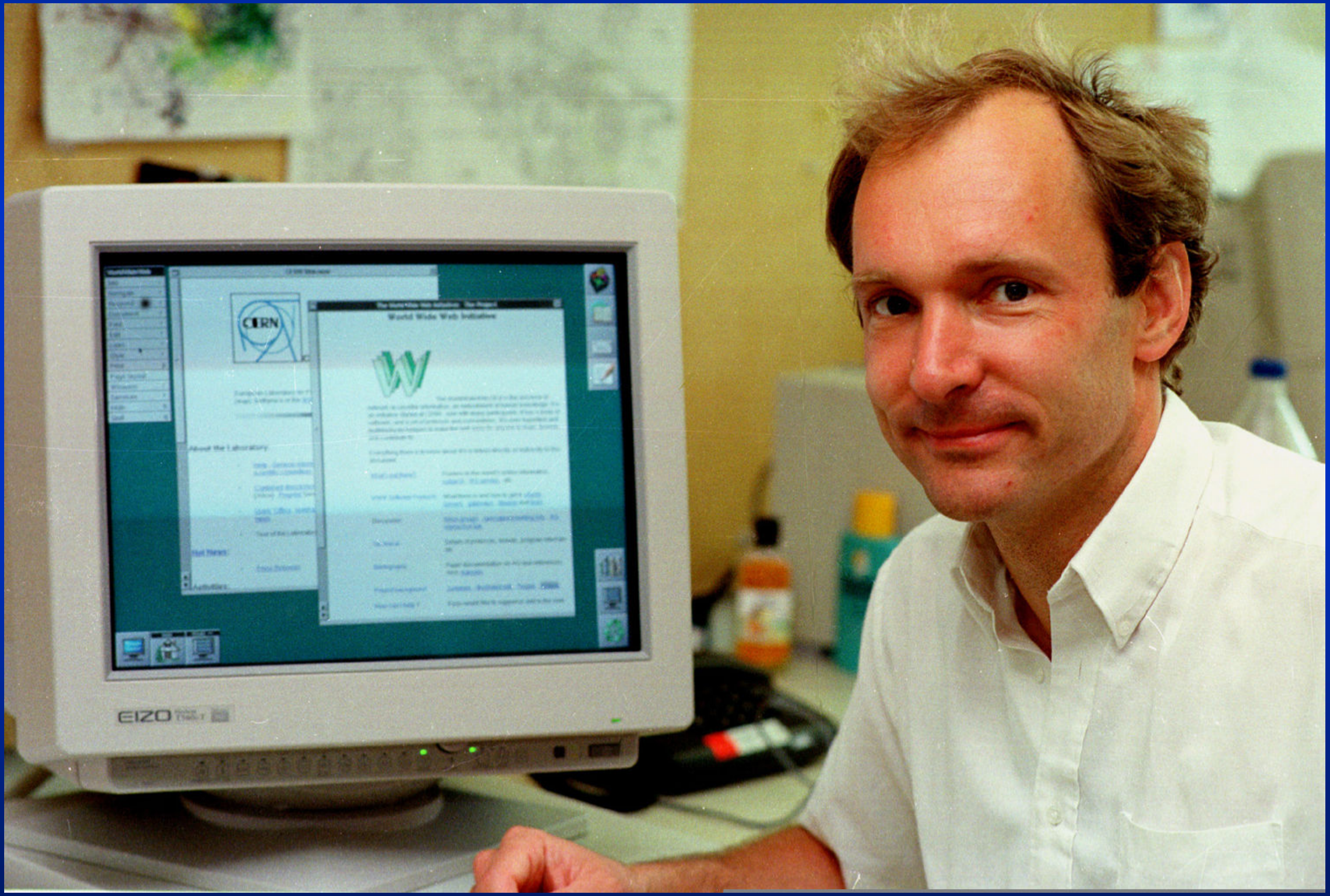
100% SCIENCE

Telephones use electromagnetic waves to communicate

Physics in daily life


Catalyzer
Nanoparticles
GPS Navigation
Functional
Materials
Air Bag
Accelaration
Sensors
Cosmetics
TiO2 Nanoparticle
Pace Maker
Li-Batteries
New Materials for Energy
Artificial Hips
Biocompatible
Materials
Mobile Phone
SAW Structures
Glasses and Coatings
Optical Materials
UV Filter
Digital Camera
CCD Chip
Artificial Lens
Biocompatible
Polymers
Intelligent Credit Card
Integrated Circuits
Exact Time via satellite
Semiconductíng devices
Micro-Batteries
Bike Frame
Carbon Fibres
Composite Materials
GMR Read Head
Magnetic
Multilayers
LED Display
Photonic Materials

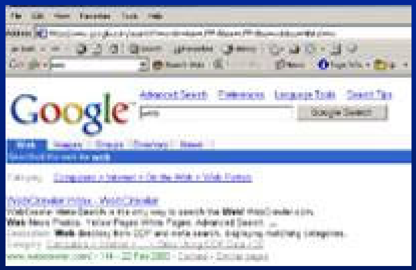
And have you heard of the… Web?



What is the GRID?

The World Wide Web provides seamless access to information that is stored in many millions of different geographical locations

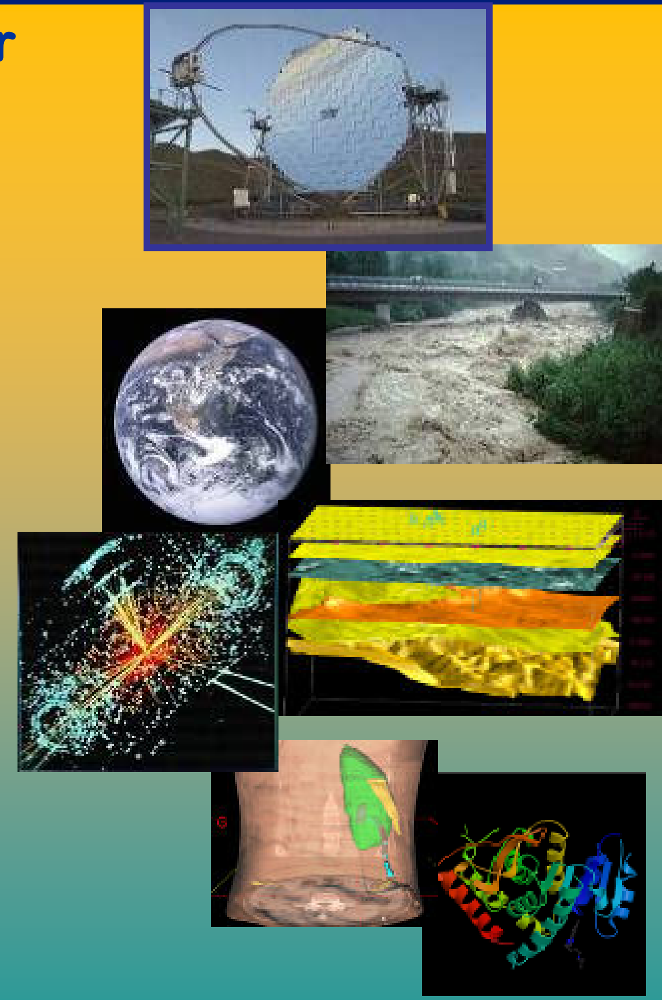
In contrast, the Grid is an emerging infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe.



Applications of EGEE

Multitude of applications from a growing number of domains

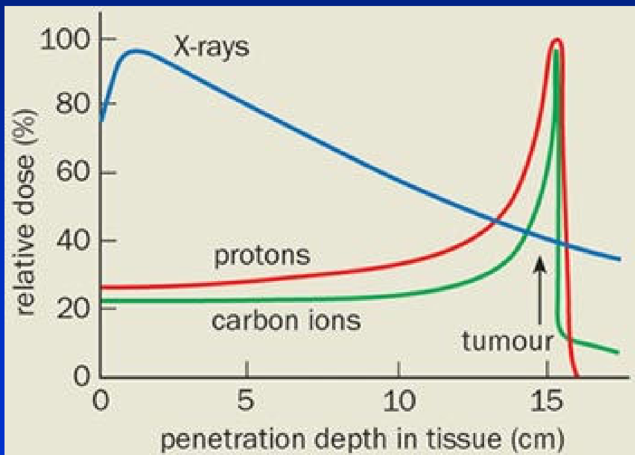
- Archeology
- Astronomy & Astrophysics
- Civil Protection
- Computational Chemistry
- Earth Sciences
- Financial Simulation
- Fusion
- Geophysics
- High Energy Physics
- Life Sciences
- Multimedia
- Material Sciences
- …

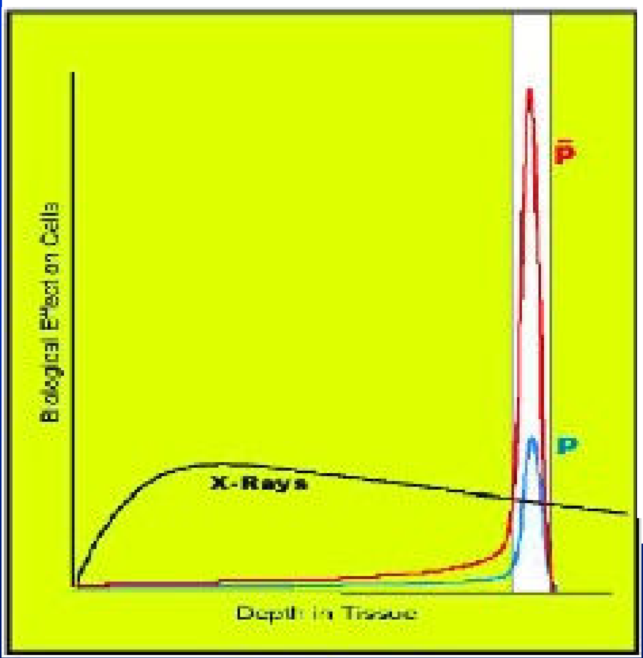


Infrastructure used by >5000 researchers
- submitted ~20 millions jobs in 2006

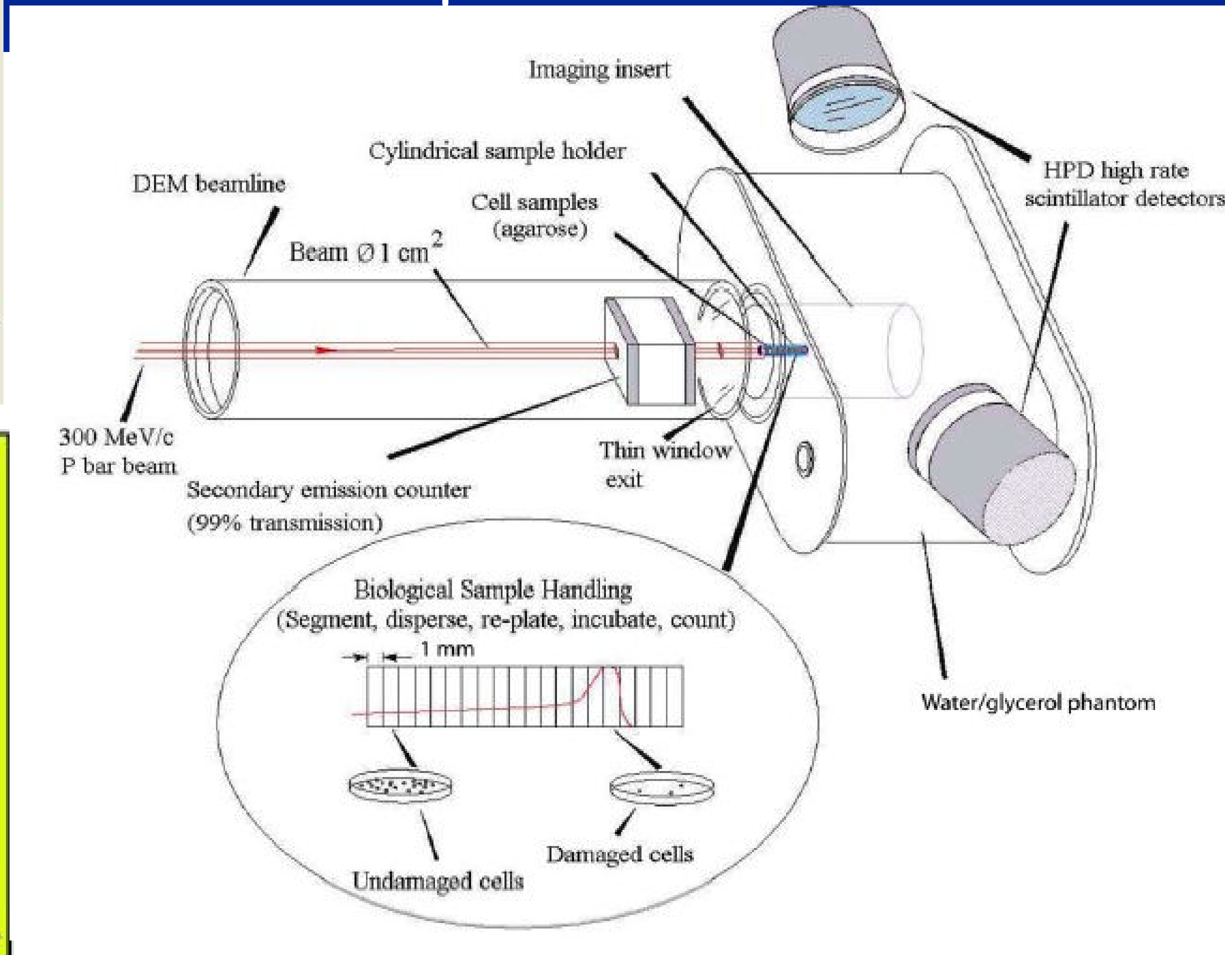
Medical Spin off

Antimatter application: tumor therapy?



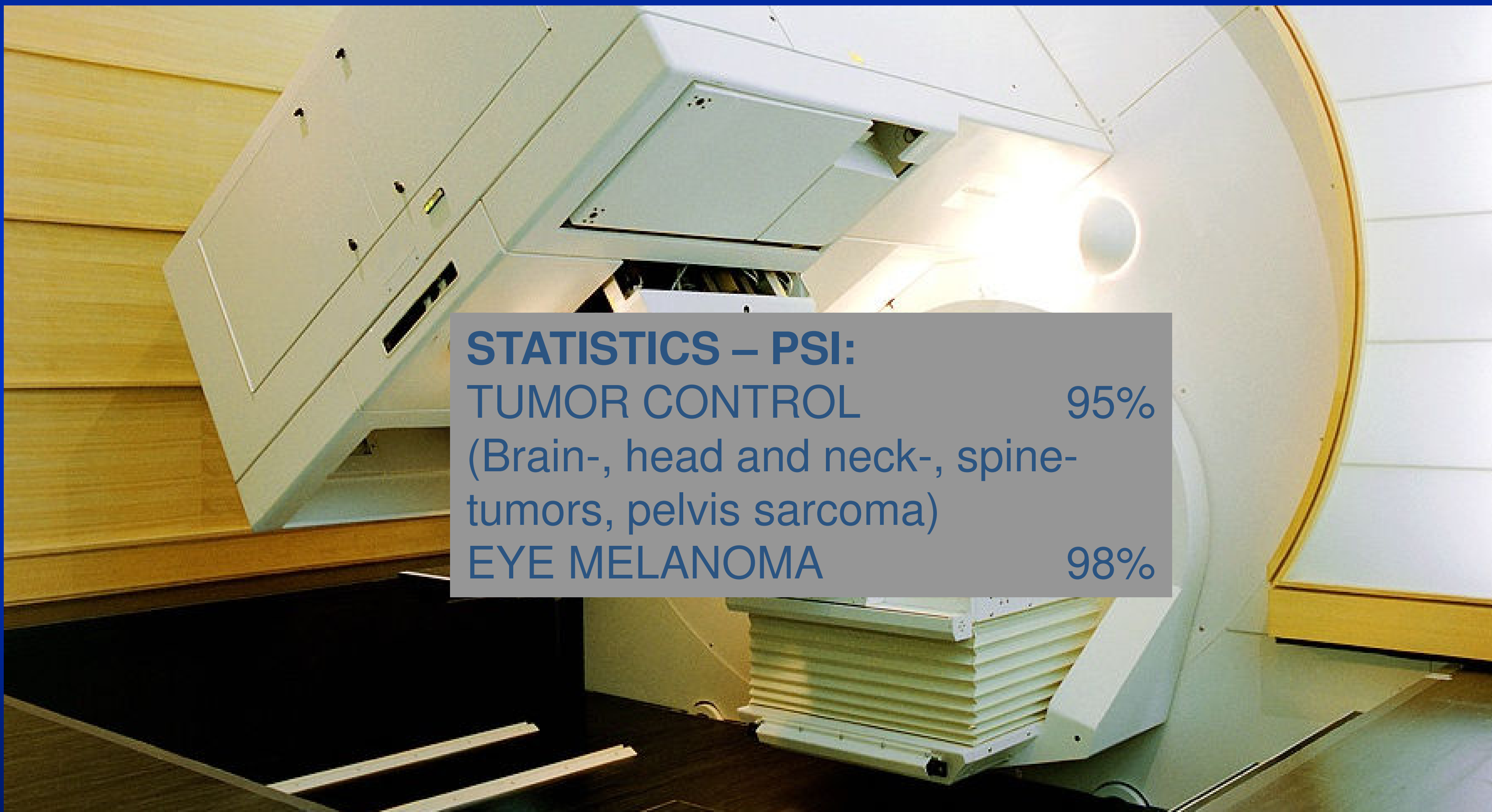


ACE experiment at CERN



*) Antiproton Cell Experiment

Cancer treatment with proton beam

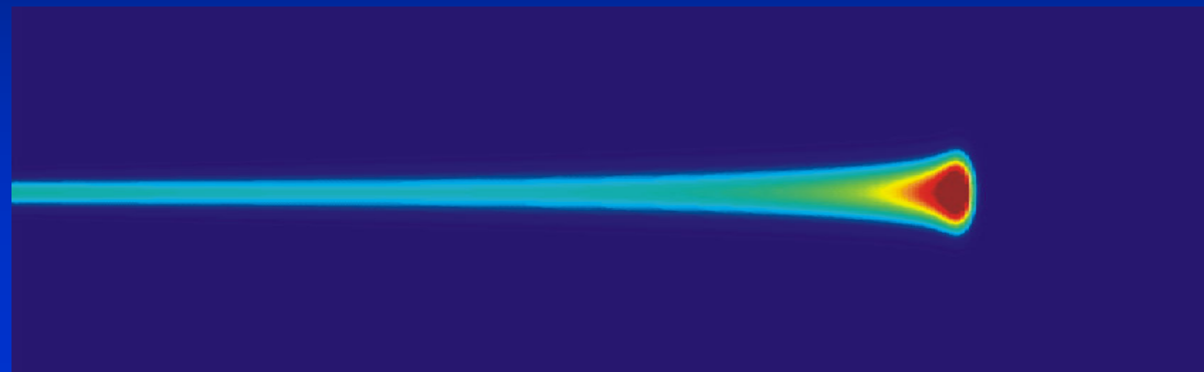


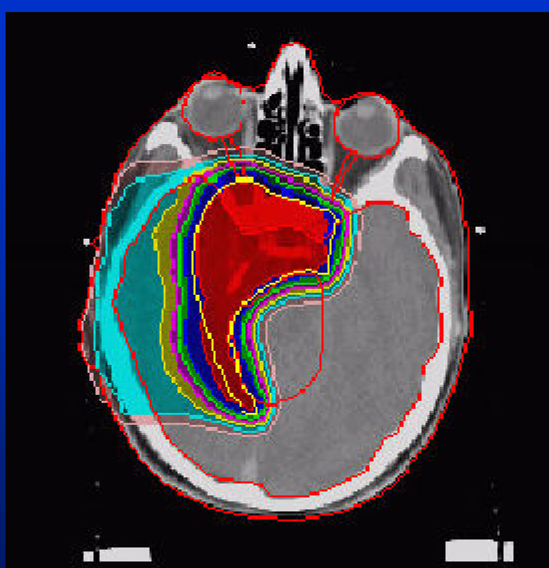
STATISTICS – PSI:

TUMOR CONTROL (Brain-, head and neck-, spine-tumors, pelvis sarcoma)	95%
EYE MELANOMA	98%

BRAGG PEAK

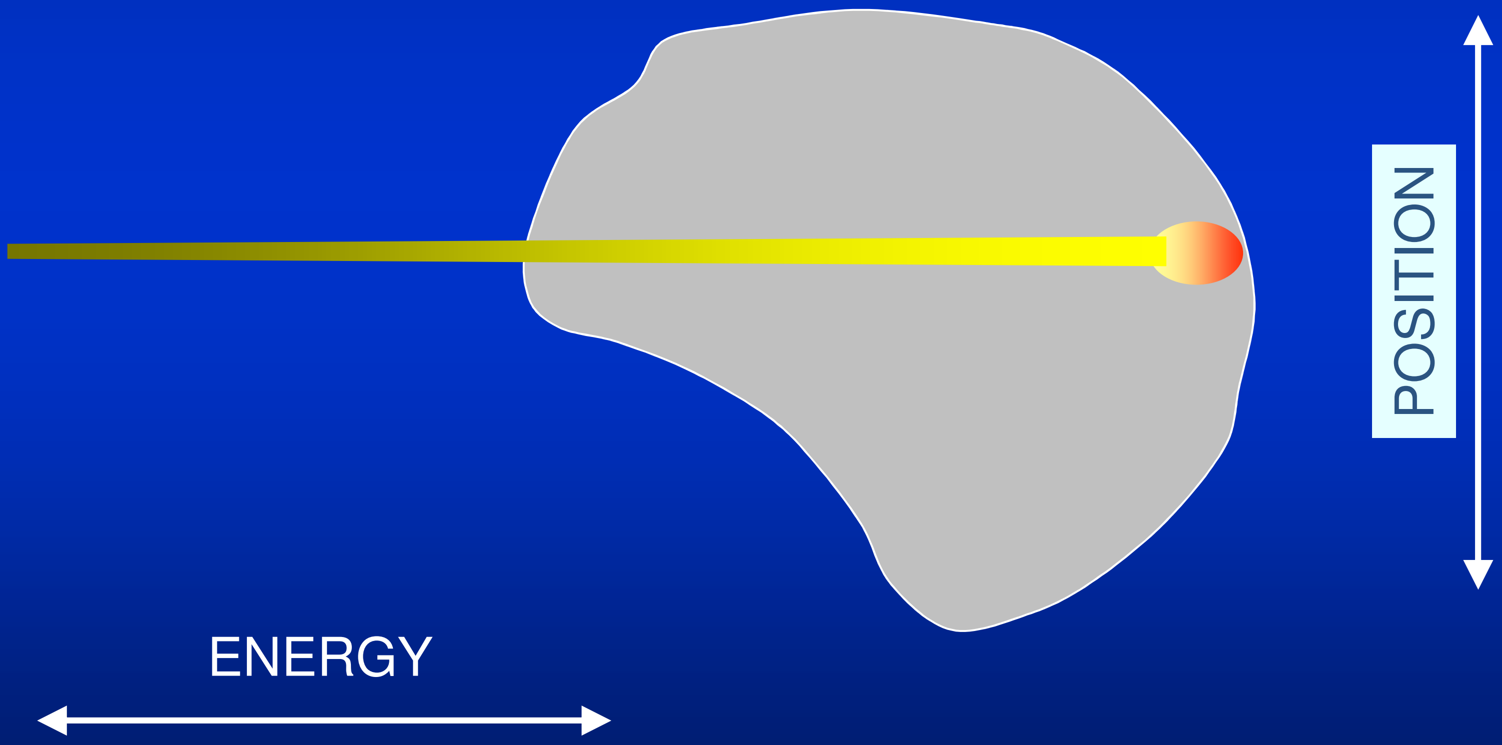
PROTON BEAM →



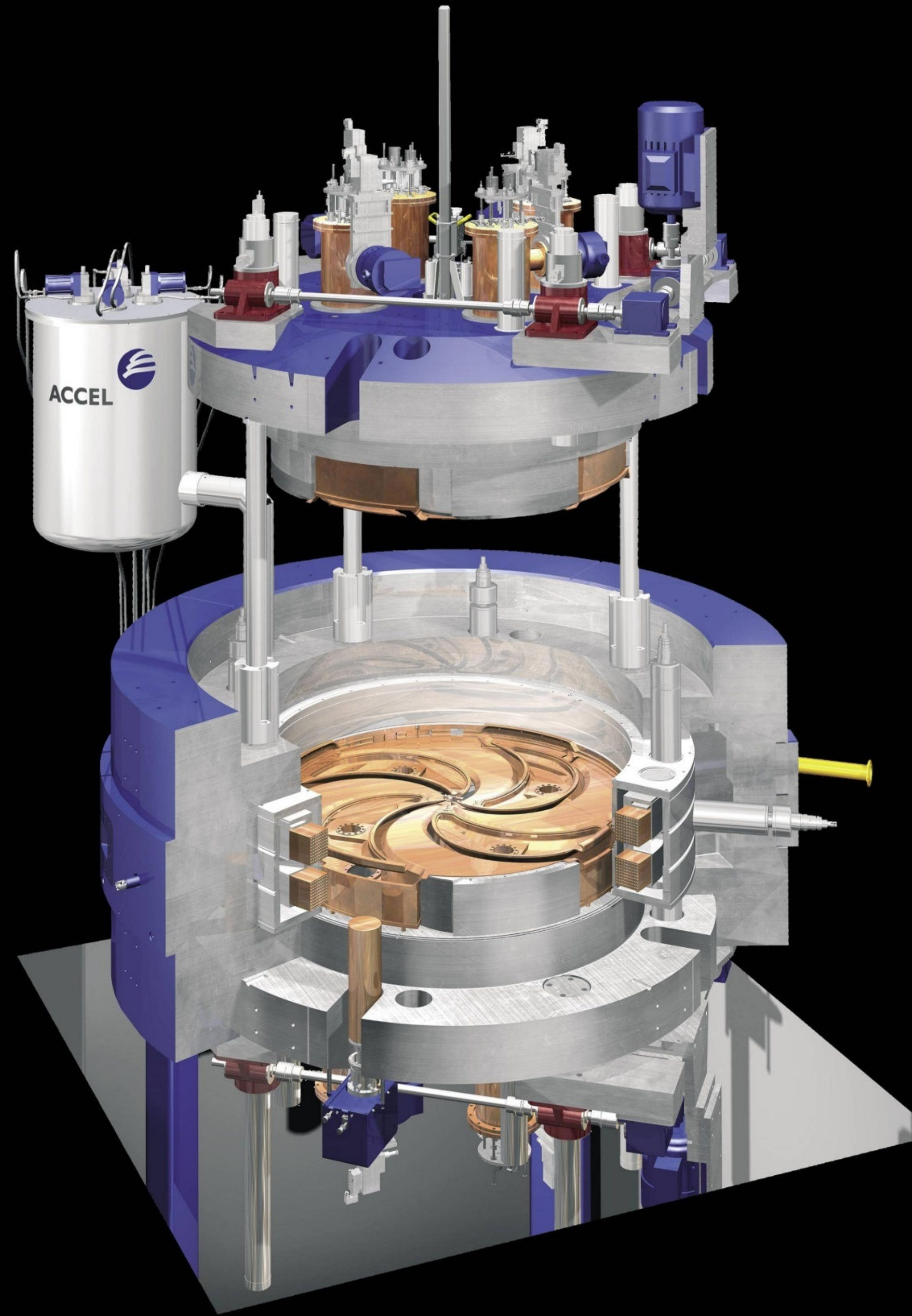


… ALLOWS THE TREATMENT OF DEEP INSIDE LYING TUMORS WITH BEST PROTECTION OF THE SURROUNDING

SPOT SCANNING

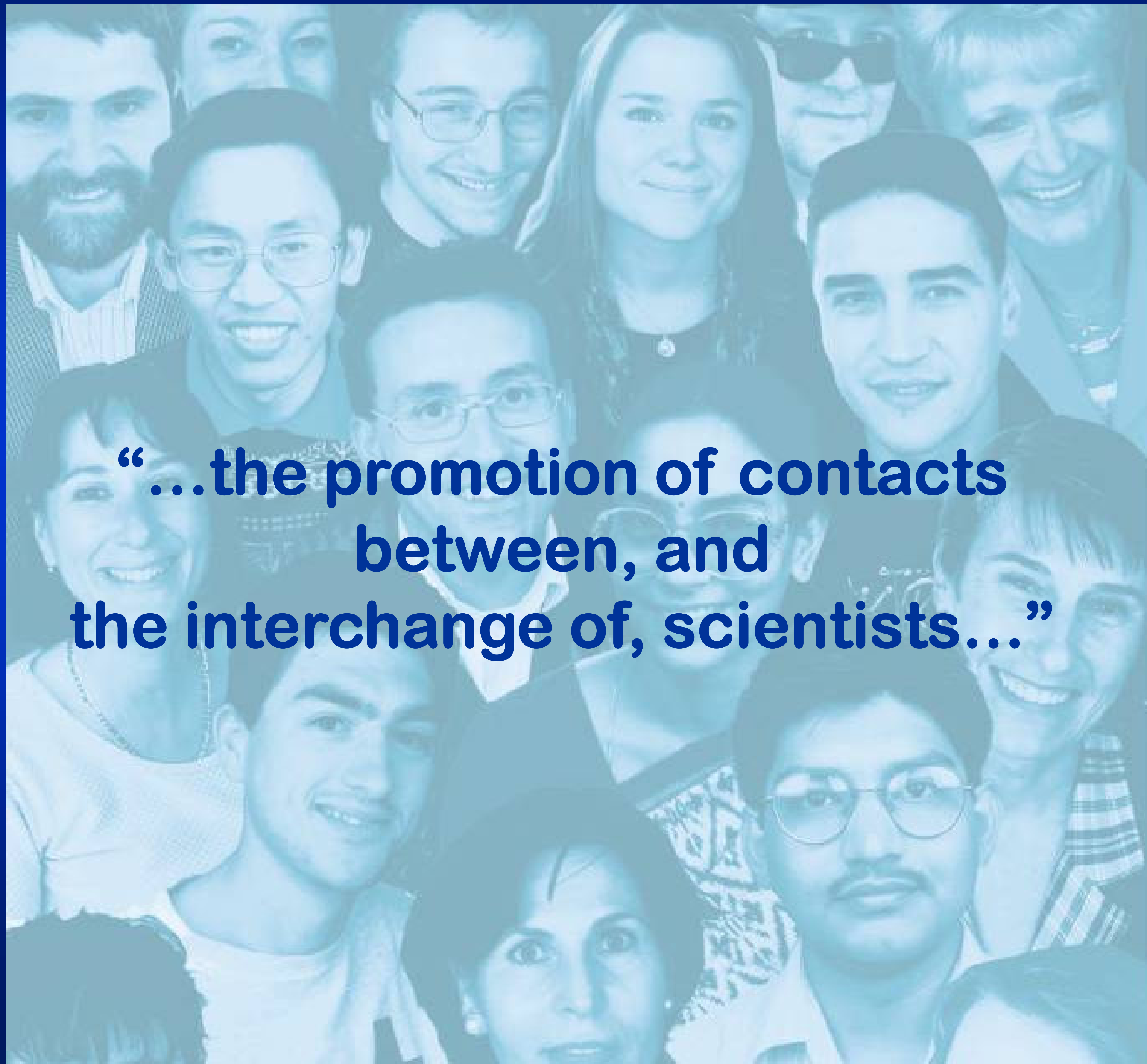


Superconducting cyclotron COMET at PSI



CERN as an Educator

Bringing Nations Together



"…the promotion of contacts between, and the interchange of, scientists…"